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Significance of settling model structures and parameter subsets in modelling WWTPs under wet-weather flow and filamentous bulking conditions

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ABSTRACT

Current research focuses on predicting and mitigating the impacts of high hydraulic loadings on centralized wastewater treatment plants (WWTPs) under wet-weather conditions. The maximum permissible inflow to WWTPs depends not only on the settleability of activated sludge in secondary settling tanks (SSTs) but also on the hydraulic behaviour of SSTs. The present study investigates the impacts of ideal and non-ideal flow (dry and wet weather) and settling (good settling and bulking) boundary conditions on the sensitivity of WWTP model outputs to uncertainties intrinsic to the one-dimensional (1-D) SST model structures and parameters. We identify the critical sources of uncertainty in WWTP models through global sensitivity analysis (GSA) using the Benchmark simulation model No. 1 in combination with first- and second-order 1-D SST models. The results obtained illustrate that the contribution of settling parameters to the total variance of the key WWTP process outputs significantly depends on the influent flow and settling conditions. The magnitude of the impact is found to vary, depending on which type of 1-D SST model is used. Therefore, we identify and recommend potential parameter subsets for WWTP model calibration, and propose optimal choice of 1-D SST models under different flow and settling boundary conditions. Additionally, the hydraulic parameters in the second-order SST model are found significant under dynamic wet-weather flow conditions. These results highlight the importance of developing a more mechanistic based flow-dependent hydraulic sub-model in second-order 1-D SST models in the future.

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1. Introduction

Activated sludge systems are the most widely used biological solutions in wastewater treatment plants (WWTPs) around the world. A conventional activated sludge unit consists of bioreactors connected to secondary settling tanks (SSTs). In bioreactors, microorganisms suspended as flocs (activated sludge) grow on organic and inorganic constituents (pollutants) in wastewater, and they are separated from the treated water in the SSTs by means of gravity sedimentation. A part of the sludge is recycled from the bottom of the SST to the bioreactors to maintain the biomass concentration in the bioreactor optimal for efficient conversion of the organic matter. In fact, SSTs fulfil a triple role in the activated sludge units, acting as a clarifier, a sludge thickener, and during wet-weather conditions as a sludge storage tank.

The solids transport in an SST is primarily influenced by the gravity-induced motion of particles. Additionally, the solids are carried downwards or upwards by the convective bulk flow generated by the recycle- and overflow, respectively. Besides hydraulic disturbances under wet-weather conditions, poor settling of activated sludge as a result of excessive filamentous bacteria growth can also hinder the effective operation of SSTs. These factors can influence the adopted recycle flow rate and, moreover, limit the maximum permissible flow rate entering the system (Ekama et al., 1997). Therefore, SSTs are considered the major hydraulic bottleneck of activated sludge units.

A numerical model of an activated sludge unit generally consists of an Activated Sludge Model, ASM (Henze et al., 2000) describing the biological processes in reactors, coupled with a model describing the solids-liquid separation process in the SSTs. For dynamic simulations of WWTPs, one-dimensional (1-D) SST models are predominantly used. These models predict the sludge blanket dynamics in the tank, particularly in case of solids shifts from the bioreactors during wet-weather flow conditions. The most widely used 1-D SST model is the first-order model developed by Takács et al. (1991). In the last two decades, second-order models that include an explicit dispersion term in the mass balance have been developed to overcome the numerical limitations of the first-order models (Bürger et al., 2011; Chancelier et al., 1994; David et al., 2009; De Clercq et al., 2003; Jeppsson and Diehl, 1996; Joannis et al., 1999; Plósz et al., 2007, 2011; Watts et al., 1996). The second-order models with a flow-dependent dispersion term (e.g. Plósz et al., 2007; Watts et al., 1996) have the advantage of simulating the hydraulics of SSTs in a wider range of dynamic flow conditions. In our recent study, consisting of a global sensitivity analysis (GSA) using the Benchmark simulation model No. 2, BSM2 (Ramin et al., 2014), we show that selecting either of the 1-D SST type models results in different optimal parameter sub-sets for the calibration of biological and sludge treatment processes in a plant-wide model. Furthermore, we discuss the limitations of first-order SST models with relevance to the calibration of WWTP models.

Unfortunately, despite the advantages of their application for WWTP simulations, the second-order 1-D SST models have not yet found their way into common practice. A possible reason for this may be the perceived difficulty of their calibration mostly due to the lack of guidelines. In the scientific and technical report of the International Water Association (IWA) by Rieger et al. (2012), which aims to promote good modelling practice (GMP) in activated sludge modelling, guidelines are provided to select, set up, calibrate and validate the ASM-type models. However, the GMP protocol only gives very brief guidelines on the selection of SST models.

The aim of this study is to supplement the GMP protocol with practical findings on the calibration of 1-D SST models for dynamic WWTP simulations. In this regard, we performed comparative evaluations of first- and second-order 1-D SST models in WWTP simulations under ideal and non-ideal flow (dry and wet weather) and settling (good settling and bulking) boundary conditions by means of global sensitivity analysis (GSA). GSA has previously been used as an effective tool to identify sources of uncertainty in WWTP models associated with model parameters (Benedetti et al., 2012; Cosenza et al., 2013a; Mannina et al., 2006; Neumann et al., 2009; Saltelli et al., 2006; Sin et al., 2011; Sweetapple et al., 2013). In this study, we employ GSA to perform an assessment of sensitivity of WWTP model outputs to uncertainties intrinsic to the SST model structures and parameters under the different boundary conditions imposed on the WWTP simulation model.

The main objectives of this paper are (i) to assess how the imposed flow and settling boundary conditions can influence the sensitivity of WWTP model outputs to the SST model parameters, (ii) to investigate if the influence of such boundary conditions vary, depending on whether the first- or second-order SST models are used, and finally (iii) based on GSA results, propose potential parameter sub-sets for the calibration of WWTP models using first- and second-order SST models under ideal and non-ideal boundary conditions.

2. A Brief overview OF 1-D SST modelling

2.1. *Engineering objectives and boundary conditions*

In general, engineering objectives, requiring some form of SST modelling, comprise SST design (preliminary or detailed assessment), SST trouble-shooting, sizing bioreactors combined with SST, WWTP modelling and decision support, and design of WWTP control. Once the engineering objective is defined, practitioners should specify the boundary conditions of the SST system in terms of design (i.e. simple: surface and depth; more detailed: also the inner structure of SST and sludge collection mechanism), the flow-rate conditions (constant, dry weather, dry and wet weather), and the settling characteristics (optimum and/or bulking). In WWTP modelling, 1-D SSTs can only account for simple design boundary conditions (i.e. average depth, surface area).

Idealised flow and settling conditions are typically used for WWTP design purposes. On the other hand, for model-based WWTP optimisation objectives, plausible and realistic operational scenarios (e.g., wet weather and bulking events) can be considered (Plósz et al., 2012).

2.2. *Target output variables*

SST model output variables should be selected, depending on the engineering objectives. For 1-D SST models, target output