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A sensitivity and model reduction analysis of one-dimensional secondary settling tank models under wet-weather flow and sludge bulking conditions

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HIGHLIGHTS

- Parameter subsets suitable for the Bürger–Diehl model calibration are identified.
- Parameter interactions are evaluated based on GSA results.
- The imposed simulation conditions impact the sensitivity of model outputs to parameters.
- Reliable reduction of the Bürger–Diehl model can be achieved based on GSA results.
- Uncertainty analysis can be used to evaluate the Bürger–Diehl model reductions.

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ABSTRACT

In this study, we provide the sensitivity and reduction analysis of the current, most advanced one-dimensional (1-D) secondary settling tank (SST) model, the Bürger–Diehl model, under non-ideal flow and settling conditions. Parameter subsets suitable for the Bürger–Diehl model calibration are identified. For example, under the wet-weather condition, all model parameters, except f_n and $D_{c,0}$, are influential to SST performance. When filamentous bulking occurs, the outputs of the Bürger–Diehl model are most sensitive to the hindered settling parameters, v_0 and r_h. In terms of parameter interactions, strong interactions are found among parameters in predicting C_e. However, for C_u, SI and Flux_{op} under the bulking condition, the Bürger–Diehl model is almost additive with negligible parameter interactions. Moreover, the sensitivity of the Bürger–Diehl model outputs to parameters is highly impacted by the imposed simulation conditions, thus resulting in different parameter subsets for model calibration. For example, under the wet-weather condition, the compression settling parameters can be as important as the hindered settling parameters, while bulking of the sludge greatly increases the influence of the hindered settling parameters (v_0 and r_h), and decreases the influence of the compression settling parameters. In terms of model reduction, reliable reduction of the Bürger–Diehl model can be achieved based on GSA results. For example, under the bulking condition, the Bürger–Diehl model can be reduced to the hindered–dispersion model regardless to model outputs. The reliability of the Bürger–Diehl model reduction can be evaluated based on uncertainty, and unreliable reduction can negatively impact the decision making in SST design and control.

1. Introduction

The activated sludge process is the most widely used technique to remove organic matter and reduce nutrients such as nitrogen and phosphorus in wastewater treatment plants (WWTPs). Generally, efficient solids–liquid separation techniques are needed to provide low turbidity effluent by removing the biomass from the liquid, and the secondary settling tanks (SSTs), where biomass is settled by gravity, are the most commonly used [1]. Mathematical modeling approaches, where the activated sludge models, comprised of a set of ordinary differential equations (ODEs), are coupled with the SST models, comprised of a set of partial differential equations (PDEs), are being increasingly used in wastewater treatment process studies for three purposes (1) learning, which means the model simulation results are able to improve

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the understanding of wastewater treatment process; (2) design, the model can be used to evaluate various design alternatives via simulation, and (3) process optimization and control, simulating different sceneries to optimize the process efficiency and avoid possible failure problems [2–4].

The family of activated sludge models [5–7] provide a comprehensive description of the significant biological processes of the activated sludge system, and are widely accepted in the research and industrial communities as a useful tool for scientific study and practical applications. However, compared with the well-developed scientific knowledge on characterizing the metabolic processes and contaminant removal in the bioreactor, various settling behavior occurring in the SST still remain poorly understood, thus making the SST model a potential error source in process simulation [8]. The one-dimensional (1-D) 10-layer model, also known as the Takács model [9], is the most commonly used SST model and has been implemented in most commercial simulators as a reference model. Although the Takács model has achieved a degree of success in predicting the SST performance, its shortcomings are not negligible, such as the insufficient description of various settling behaviors and inaccuracy of numerical solutions, which have been demonstrated in previous studies [8,10–13].

In last two decades, to compensate for the limitations of the Takács model, several advanced SST models have been developed as alternatives, which can be classified into three groups based on their advantages:

1. First-order hindered-only models with reliable numerical techniques: for these models, the model formula remains the same as the Takács model, considering only the hindered settling behavior, but using more reliable numerical techniques. Reliable techniques such as the Godunov numerical flux, the Yee–Roe–Davis (YRD) numerical flux, and finer discretization levels (more than 30-layers), are used to construct both numerically and physically acceptable solutions [10,13,14].
2. Second-order hindered–compression models additionally accounting for compression settling: the improved understanding of activated sludge rheology has facilitated the development of phenomenological theory of sedimentation-consolidation. The phenomenological theory is then expressed in the compression model, which allows a more rigorous description of the compression settling behavior [15,16]. Compared with the hindered-only model, the hindered–compression model is expected to provide more realistic predictions of the sludge blanket level and the underflow concentration.
3. Second-order hindered–dispersion models additionally accounting for hydraulic dispersion: for these models, an explicit hydraulic dispersion term is added to the model formula to account for the potential impact of hydraulics on the biomass settling behavior [17,18]. The hydraulic dispersion model possesses the advantage of simulating the hydraulics of SSTs over a wider range of dynamic flow conditions [17,19]. From the numerical point of view, adding the explicit flow-dependent dispersion term also decreases the difficulty in solving the hindered–dispersion model.

Recently, a new 1-D SST model, the Bürger–Diehl model (the hin dered–compression–dispersion model), has been presented [20], which accounts for phenomena that may impact the SST behavior, such as hindered settling, compression settling and hydraulic dispersion. The Bürger–Diehl model is also based on the reliable numerical solution of its governing model formula by appropriate methods [21]. Therefore, the Bürger–Diehl model is able to provide more realistic predictions of the SST performance.

Despite the advantages of the Bürger–Diehl model, its practical application is limited, which can be attributed to two main reasons:

(1) The difficulty of calibration: great efforts have been made to facilitate model calibration, for example by evaluating the hindered-only and hindered–dispersion models, Ramin et al. [18,22] identified the potential parameter subsets suitable for the calibration of WWTP models under various simulation conditions. However, calibrating the 1-D SST models accounting for the compression settling still remains a challenge due to the insufficient understanding of the influence of compression settling on the SST performance.

(2) The increased implementation complexity and computation burden: technically, the currently used hindered-only, hindered–compression and hindered–dispersion models can be considered as the sub-models of the Bürger–Diehl model, and their successful applications in SST simulation implies that the Bürger–Diehl model in some cases can be reduced to these sub-models without sacrificing the quality of prediction. However, how to reliably reduce the Bürger–Diehl model, particularly under non-ideal flow and settling conditions, still remains unclear.

In this study, we provided a comprehensive sensitivity and model reduction analysis of the Bürger–Diehl model under non-ideal flow and settling conditions. The Benchmark Simulation Model No. 1 (BSM1) [23] is used as the simulation platform, because of its well documented model inputs. The influence of the uncertainty of model parameters to the variance of model outputs, such as the sludge blanket level, is quantified by using global sensitivity analysis (GSA), and the reliability of the Bürger–Diehl model reduction is evaluated based on uncertainty analysis.

The main objectives of this paper are (i) identify the suitable parameter subsets for the Bürger–Diehl model calibration under non-ideal flow and settling conditions; (ii) evaluate the influence of imposed flow and settling conditions on the sensitivity of the Bürger–Diehl model outputs to the parameters; (iii) demonstrate how reliable reduction of the Bürger–Diehl model can be achieved based on GSA results; (iv) assess the reliability of the Bürger–Diehl model reduction for different modeling purposes based on uncertainty analysis results.

2. Materials and methods

2.1. Model structure and simulation condition description

As shown by Fig. 1, BSM1 is used as the simulation platform, where ASM1 is combined with the SST model to describe the biological and settling processes of the activated sludge system. For further details about ASM1, the reader is referred to literature [5]. With regards to the SST model, the Bürger–Diehl model is used to replace the Takács model.

The formula of the Bürger–Diehl model can be expressed as Eq. (1) on the basis of the mass and momentum conservation:

$$\frac{\partial C}{\partial t} + \frac{\partial}{\partial x}F(C,x,t) = \frac{\partial}{\partial x}\left((d_{\text{disp}}(v_{ov}) + d_{\text{comp}}(C))\frac{\partial C}{\partial x}\right) + \frac{Q_f(t)C_f(t)}{A}\delta(t) \quad (1)$$

where C is the solids concentration, t is time, x is the depth from the feed layer, v_{ov} is the overflow velocity, Q_f is the feed flow rate, A is the SST surface area, C_f is the feed solids concentration, δ is the Dirac delta distribution and the transport flux F can be written as Eq. (2) [24]: