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Uncertainty analysis in WWTP model applications: A critical discussion using an example from design

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ABSTRACT

This study focuses on uncertainty analysis of WWTP models and analyzes the issue of framing and how it affects the interpretation of uncertainty analysis results. As a case study, the prediction of uncertainty involved in model-based design of a wastewater treatment plant is studied. The Monte Carlo procedure is used for uncertainty estimation, for which the input uncertainty is quantified through expert elicitation and the sampling is performed using the Latin hypercube method. Three scenarios from engineering practice are selected to examine the issue of framing: (1) uncertainty due to stoichiometric, biokinetic and influent parameters; (2) uncertainty due to hydraulic behaviour of the plant and mass transfer parameters; (3) uncertainty due to the combination of (1) and (2). The results demonstrate that depending on the way the uncertainty analysis is framed, the estimated uncertainty of design performance criteria differs significantly. The implication for the practical applications of uncertainty analysis in the wastewater industry is profound: (i) as the uncertainty analysis results are specific to the framing used, the results must be interpreted within the context of that framing; and (ii) the framing must be crafted according to the particular purpose of uncertainty analysis/model application. Finally, it needs to be emphasised that uncertainty analysis is no doubt a powerful tool for model-based design among others, however clear guidelines for good uncertainty analysis in wastewater engineering practice are needed.

Abbreviations: ANOVA, analysis of variance; ASM, activated sludge model; ASM1, activated sludge model no. 1; BNR, biological nutrient removal; BOD_5, biochemical oxygen demand; BSM1, benchmark simulation model no. 1; CDF, cumulative distribution function; COD, chemical oxygen demand; DO, dissolved oxygen; HRT, hydraulic retention time; IWA, International Water Association; k_La, oxygen transfer coefficient (day^{-1}); LHS, Latin hypercube sampling; MLSS, mixed liquor total suspended solids; NH_4-N, ammonium nitrogen; PI, proportional–integral; SRC, standardised regression coefficients; SRT, sludge retention time; SS, suspended solids; TN, total nitrogen; TSS, total suspended solids; WWTP, wastewater treatment plant.

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1. Introduction

The interest in performing uncertainty analysis of wastewater treatment plant (WWTP) models particularly for design purposes has been demonstrated in the studies of Rousseau et al. (2001), Bixio et al. (2002), Benedetti et al. (2008) and McCormick et al. (2008). Flores-Alsina et al. (2008) applied uncertainty analysis for comparing different control strategy options on a WWTP model, and demonstrated that considering uncertainty has important implications on decision making, e.g. which controller is better for the WWTP in question. These studies have in common that they all demonstrated potential benefits of uncertainty analysis, e.g. uncertainty analysis offers a quantitative basis to justify safety factors as well as better informed decision making thereby contributing to cost-savings in engineering projects. That said, the field of uncertainty analysis of WWTP models is still in its infancy as there is a range of issues that need further research, as reflected in the recent WWTMod2008 workshop on uncertainty (Belia et al., 2008).

Application of activated sludge models is typically based on a number of assumptions relating to wastewater composition, influent load profiles and values of various parameters of the specified model, e.g. the activated sludge model no. 1 (ASM1) (Henze et al., 2000; Sin et al., 2005, 2008). Uncertainty about these parameters is called input uncertainty as these model parameters are fed into the model to make a prediction. The input uncertainty may be characterised by a certain range of values reflecting the limited knowledge about the exact value of the parameter in question. For instance, the value of the aerobic heterotrophic yield in ASM1 is specified as being in the range from 0.6 to 0.7 g COD (g COD)$^{-1}$ (Henze et al., 2000) rather than having an exact value.

Uncertainty is however not limited to input uncertainty. Indeed, there are different sources of uncertainty affecting model predictions (McKay et al., 1999; Walker et al., 2003; Refsgaard et al., 2007). Various sources of uncertainty may be grouped as (McKay et al., 1999): (i) input (subjective) uncertainty – that reflects lack of knowledge about the model inputs as illustrated above; (ii) structural uncertainty – that relates to the mathematical form of the model (models are approximations to systems rather than an exact copy); and (iii) stochastic uncertainty – this may be a component of the model itself (e.g. a random process to model failure events of pumps, etc).

In general, uncertainty analysis is concerned with propagation of the various sources of uncertainty to the model output. The uncertainty analysis leads to probability distributions of model outputs, which are then used to infer the mean, variance and quantiles of model predictions (Helton and Davis, 2003). The sensitivity analysis, on the other hand, aims at identifying and quantifying the individual contributions of the uncertain inputs to the output uncertainty. While uncertainty and sensitivity analysis should preferably be performed in tandem (Saltelli et al., 2008), we conduct the sensitivity analysis in an accompanying study (Sin et al., in preparation) in order to keep this study focused on the framing of the uncertainty analysis only (see below).

This study aims at analyzing some of the critical issues involved in the uncertainty analysis of models developed in the field of wastewater treatment, particularly the issue of framing and how it fundamentally affects the interpretation of the results of the uncertainty. The framing is broadly understood as the context in which uncertainty analysis is performed, and the way the problem to be addressed by the uncertainty analysis is set up and solved. It refers to the assumptions and choices made that define the system boundary (often related to the mathematical model selected to represent the system), identification and characterisation of sources of uncertainty in the system and also the methodology and its underlying assumptions used for quantifying the uncertainty.

The objective of this study is to demonstrate that the results obtained from uncertainty analysis are dependent on the framing. To set the stage for the discussions, first the uncertainty analysis techniques are introduced within the context of WWTP model applications. Next the results of uncertainty analysis are critically discussed in view of the framing issue. To achieve these objectives a narrow but clear setting for the uncertainty analysis is defined as follows: we focus on prediction uncertainty typically encountered when designing a plant. The benchmark simulation model no. 1 (BSM1) plant layout and its operational and influent characterisation is selected as a case study (Copp, 2002). The problem statement in this design setting is formulated as follows: given a plant layout, an operational configuration and an influent profile, how can an engineer predict the uncertainty of the main performance criteria considered in plant design – e.g. effluent ammonium concentration, sludge production and energy consumption – that arise due to input uncertainty, e.g. influent characterisation and fractionation, aeration and biokinetic parameters, etc? Finally, the framing issue is evaluated using three different scenarios for the framing: (i) uncertainty about stoichiometry, biokinetics and influent fractions; (ii) uncertainty about plant hydraulics and mass transfer parameters; and (iii) uncertainty due to both (i) and (ii), i.e. stoichiometry, biokinetics, influent fractions, hydraulics and mass transfer. These scenarios represent real-world engineering questions as outlined in Box 1, which are meant to provide a context from engineering practice.

2. Materials and methods

2.1. Scenarios for framing uncertainty analysis

For framing the uncertainty analysis in a WWTP design setting, the three engineering scenarios outlined in Box 1 are formulated. To that end, all other assumptions pertaining to uncertainty analysis (e.g. system boundary, problem statement, the methodology, etc.) are kept unchanged, while different assumptions are used when identifying the sources of uncertainty in the system. These are summarised in Table 1. Accordingly, scenario 1 considers uncertainty only in the stoichiometric, biokinetic and influent fractionation parameters, while scenario 2 considers uncertainty in the hydraulics and mass transfer characteristics of the plant. Last,