A practical and sound model calibration procedure applied to the WWTP of Eindhoven

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Abstract: Mathematical modelling is state of the art practice in optimization of wastewater treatment plants. Notwithstanding this increased popularity, many questions remain regarding the fine tuning or calibration of the models. The authors extended and improved a calibration methodology focusing on a better description of the different sub-processes rather than force-fitting bio-kinetic parameters. This document sheds light on the application of this calibration procedure for the wastewater treatment plant of Eindhoven and highlights the many similarities but also a few differences with the GMP Unified Protocol. Improving the model description of the aeration model and the primary sedimentation model improved the simulation results of respectively ammonium NH_4 and nitrate NO_3 concentrations Following this model calibration procedure increased the understanding in the plant behaviour and the confidence in the simulation results in view of a scenario analysis for plant optimization.

Keywords: wastewater treatment; dynamic simulation; calibration

Introduction

In the European Union, the Water Framework Directive (WFD) enforces a good ecological and chemical status of all surface waters, which is to be accomplished before 2015. Many surface waters throughout Europe still do not meet the WFD requirements due to discharges of combined sewer overflows (CSO) and effluents of wastewater treatment plants (WWTP). Mathematical models provide a valuable tool for guiding the decisions towards meeting the requirements set forth by the WFD.

The Dommel is a relatively small and sensitive river flowing through the city of Eindhoven (The Netherlands) from the Belgian border (South) into the river Meuse (North), receiving discharges from the 750,000 PE wastewater treatment plant (WWTP) of Eindhoven and from over 200 combined sewer overflows (CSOs) in 10 municipalities. In summer time, the WWTP effluent equals the base flow of 1.5 m^3/s of the Dommel River just upstream the WWTP. The Dommel River does not yet meet the requirements of the European Union WFD. According to Waterboard the Dommel, which is managing the river basin including wastewater treatment , dissolved oxygen (DO) depletion, ammonia peaks and seasonal average nutrient concentration levels are the main water quality issues to be addressed (Weijers et al. 2012).

Waterboard De Dommel (Boxtel, The Netherlands) has been using models of their wastewater treatment plants (WWTPs) since the early 1990s. Since 2007, a model of the WWTP of Eindhoven (The Netherlands) is under continuous development. During the course of time models have continuously been improved through a repeating learning cycle using gained system knowledge and to be able to address more difficult model objectives (Amerlinck et al., 2013; Sin et al., 2008).

Over the years several modelling and simulation methodologies, of which a thorough review is given in MOP31 (WEF, 2013), have been postulated. One of these protocols, developed at BIOMATH (Vanrolleghem et al., 2003), focuses on calibration and validation of the biokinetic and settler models. More recent, based on a survey and in-depth discussion with several modelling experts, Rieger et al. (2012) proposed a simulation protocol (the GMP Unified Protocol), with the intention to provide a framework to allow for rigorously applying modelling and simulation without limiting the development of improvements. Five major project steps were identified and explained, i.e. (i) Project definition, (ii) Data collection and reconciliation, (iii) Plant model set-up, (iv) calibration and (v) result interpretation.

This paper reports on the practical and sound calibration procedure applied to the WWTP of Eindhoven and the similarities and differences with the GMP Unified Protocol.

Materials and Methods

With a treatment capacity of 750,000 population equivalents (PE), the WWTP of Eindhoven (The Netherlands) is the largest treatment plant of Waterboard De Dommel and the third largest in The Netherlands. The incoming wastewater is treated in three parallel lines with a maximum hydraulic load of 26,250 m^3/h, each comprised of a primary settler, a biological tank and four secondary clarifiers. An extra 8,750 m^3/h can be treated mechanically and passes a pre-settling tank before it is discharged in the river Dommel or treated in the biology when the hydraulic load is again below 26,250 m^3/h. The WWTP has a modified UCT configuration (Tchobanoglous et al., 2004) and has 7 meter deep biological tanks (**Error! Reference source not found.**). The inner ring is an anaerobic tank, the middle ring is an anoxic tank and the outer ring is a partially aerated tank. The aeration is provided by two aeration packages: a so-called summer package, which provides the aeration under normal dry weather conditions, and a so-called winter package, which provides aeration when the first package is not sufficient, mainly under rain weather conditions and cold temperatures.

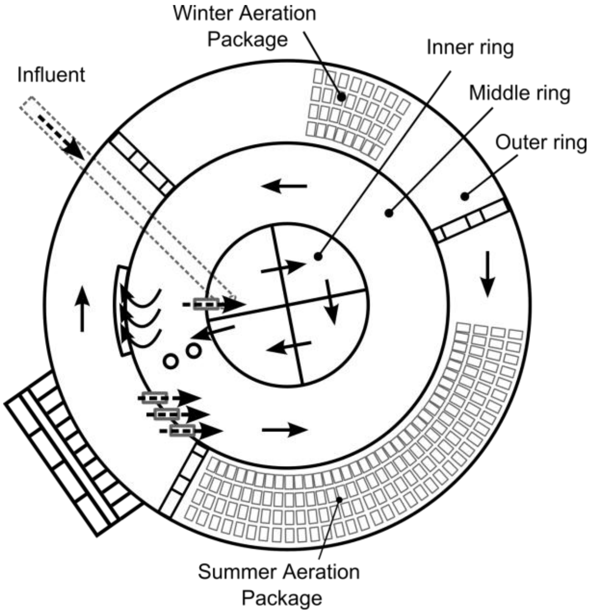

Figure 1. The circular modified UCT configuration of the activated sludge tanks at the WWTP of Eindhoven.

Over the years several versions of a process model of the plant were set up and calibrated using WEST (http://www.mikebydhi.com, Denmark; (Vanhooren et al., 2003).

The calibration procedure corresponds to the steps 2 through 4 in the GMP Unified Protocol, but focuses on a better description of the different subprocesses and not putting all calibration efforts in force-fitting biokinetic parameters. An iterative procedure is proposed where during every iteration the quality of the modelling results is improved. For well-defined biokinetic models (such as for C/N removal) deviations between simulation and experimental results are corrected by improving the model structures of the subprocesses rather than "compensating" adjustment of certain biokinetic model parameters, however safeguarding to not further over-parameterise the model. The overall aim is to identify structural uncertainties of the applied models as it is believed that the largest uncertainties are located in the description of influent, hydraulics, gas-liquid mass transfers and other physical processes such as primary and secondary settling. In fact, the biokinetic parameters are only to be changed when the default parameter set is considered not to be adequate.

The applied model calibration procedure consists of the following five major steps: (i) project definition, (ii) data collection and reconciliation, (iii) plant model set-up, (iv) calibration and validation and (v) simulation and result interpretation.

Project definition

In a start-up meeting the objectives and the necessary steps of the project are discussed and defined. The objective of this project is the optimization of the WWTP in order to improve the water quality in the Dommel River in view of meeting the requirements of the European Union Water Framework Directive, in particular looking at DO depletion, ammonia peaks and seasonal average nutrient concentration levels (Weijers et al., 2012).

Data collection and reconciliation

The data used for the calibration is a combination of online measurements, lab analysis, measurement campaigns (both organized for the purpose of operations optimization as well as for modelling purposes) and book keeping data (such as excess sludge transports to the sludge treatment plant). Using high-frequency data has increased the accuracy of the simulation results significantly (Cierkens et al., 2012) but has also put an even larger burden on data validation.

Plant model set-up

The plant model is set up based on the available design guides, plans, schemes, P&IDs and discussions with the plant staff. The biokinetic model and the model of the control logics are calibrated separately, as such avoiding bias in the calibration of either. For the calibration of the biokinetic model, the control logics are decoupled, i.e. operational data (e.g. airflow rates) logged at the wastewater treatment plant is used instead and for the calibration of the control logics the logged sensor data (e.g. oxygen and ammonium) is used as input to the control algorithms.

Calibration and validation

The calibration of the model of the Eindhoven WWTP has been a combination of expert judgment (to determine which parameters to change and which values to take) and mathematical methods (i.e. sensitivity analysis and automated parameter estimation). The overall aim during the calibration exercise was not to change biokinetic parameters values, for these changes are assumed to be mostly the result of model structure inadequacies, i.e. the largest uncertainties are located in the description of influent, hydraulics, gas-liquid mass transfers and other physical processes such as primary and secondary settling. During the calibration a step-wise approach has been used repeatedly. When new models were integrated they were individually calibrated (where possible) first on lab tests (e.g. settling tests), subsequently on full scale data of the unit process under study (e.g. the chemical phosphorus removal model) and finally integrated with the pre-existing plant model.

After calibration the result is validated on short term simulations.

Simulation and result interpretation

As a last step of the calibration cycle, the simulation results were thoroughly discussed with the wastewater technologists at the Waterboard and the outcomes were checked against the assumptions taken in the model. Additional calculations were performed for assisting the discussion, such as mass balances and a colour based analysis tool.

Results

In order to improve the predictions of ammonium removal a new model for the calculation of the oxygen transfer (from airflow rates), based on the work of Rosso et al. (2005), was implemented (Cierkens et al., 2012). In combination with feeding the measurement data of the air flow rate to the model, as such decoupling the controller model from the biokinetic model, and high frequency data for the influent characterization, dissolved oxygen and ammonium concentrations could be predicted with high accuracy (Figure 2). Despite the good fit, some of the peaks in ammonium concentration are not predicted by the model. The prediction of these peaks can probably be improved by taking into account the mixing behaviour in the model structure (Rehman et al., 2014). Within this model version, although debateable, the ammonium half saturation constant for autotrophic biomass ($K_{NH,AUT}$), which is the only biokinetic model parameter that was adjusted, was lowered compared to the default parameter value.

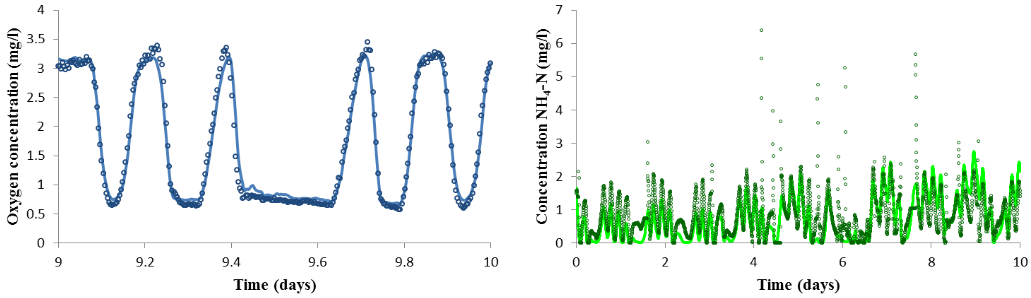

Figure 2. Fit for dissolved oxygen (left) and ammonium (right) after the adaptations to the aeration model and the model input. Lines indicate simulation results, crosses the online measurement data.

After the previous model improvement, more attention was given to the wet weather behaviour (results not shown). Hereto the primary sedimentation tank PST model was upgraded to a model taking into account the effect of the hydraulic retention time on the removal efficiency (Tay, 1982). The model of the secondary sedimentation tank was upgraded from the Takacs model (Takács et al., 1991) to the Bürger-Diehl model which has a more sound mathematical structure allowing improved prediction of the sludge blanket height and underflow concentration during wet weather (Bürger et al., 2012).

Despite the model adaptations on the aeration model and for the wet weather behaviour, the simulation results for nitrate still diverged significantly from the measurement data. In an attempt to reduce this divergence, the model of the primary sedimentation tank was extended to account for different removal efficiencies for the different suspended fractions, based on repeated measurements, during the year 2011, performed on the PSTs (Table 1). This resulted in a higher chemical oxygen demand (COD) concentration entering the activated sludge tanks as such improving the nitrate removal predictions considerably (Figure 3).

Table 1. The averaged removal efficiencies, as calculated from the measurement performed at the WWTP of Eindhoven, for five day biological oxygen demand (BOD5), chemical oxygen demand (COD), Kjeldal Nitrogen (Kj-N), total phosphorus (TP), phosphate (PO_4) and suspended solids (SS).

BOD5	COD	Kj-N	TP	PO_4	SS
34%	32%	10%	19%	49%	62%

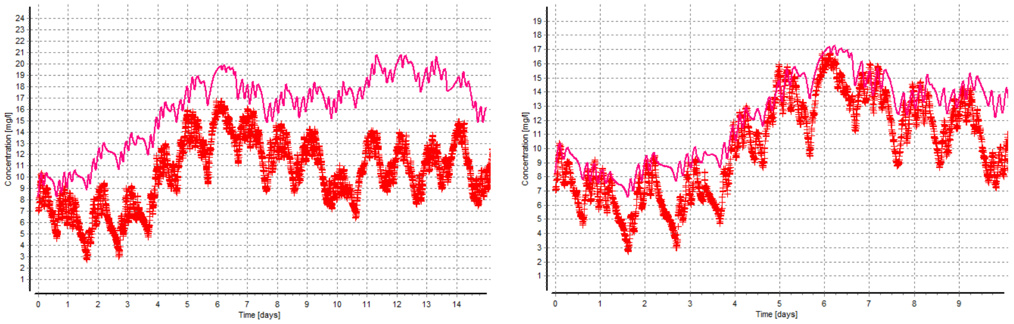

Figure 3. Improvement of nitrate model predictions with the adapted primary sedimentation tank model (right) compared to the results before the adaptations (left)**.** Lines show the simulation results, crosses the online measurement data.

Conclusions

The calibration procedure applied to the WWTP of Eindhoven had major similarities to the GMP Unified Protocol. Main differences were the decoupling of the controller logics from the biokinetic model and the emphasis on slightly increasing the complexity of the sub-models rather than force-fitting the biokinetic parameters. This is done in view of maintaining the predictive quality of the model under varying process conditions.

After improving the model for the aeration the simulation results match very well for DO and NH_4. The adaptation to the primary sedimentation model resulted in an improved fit for the simulation results.

Work is on-going for the short term rain weather and the long-term validation, for which the modelling work on the secondary clarifiers and a better characterization of mixing seems crucial.

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