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Immission based real-time control of the integrated urban wastewater system

Immissiegebaseerde real-time controle van het geïntegreerd stedelijk afvalwatersysteem

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Summary

In the literature review in chapter 2 of this thesis, it became clear that mathematical models are frequently applied to the individual parts of the integrated urban wastewater system (IUWS). Sewer systems, wastewater treatment plants and rivers have been modelled using both complex and simplified models. These models have been used successfully in the management of these subsystems. Different real-time control (RTC) strategies have been developed to deal with disturbances to the system (mostly stormwater in the sewer and treatment plants). In these control strategies, a typical goal is the minimisation of overflow volumes or pollution loads to the receiving water.

Lately, more attention is being paid to the joint consideration of the subsystems in order to be able to take the different interactions into account. This is also required by the Water Framework Directive (WFD) of the EU, which mainly focuses on the quality of the receiving water, which should be "good" both in terms of ecological status and chemical quality. In view of this legislation, management practices that take the immission concentration (i.e. the concentration in the river) into account are necessary in order to be able to comply with the requirements of the WFD.

Immission based RTC is one way of improving the performance of the IUWS, which allows to optimise the quality of the receiving water and uses the existing infrastructure in an optimal way. In order to design and tune such an immission based RTC strategy, a simultaneously simulating model is necessary. In this way, two way interaction between the different submodels is possible.

Three problems are encountered when developing an integrated model that is to be used for developing an integrated control strategy or for system optimisation. First, the state-of-the-art models are typically implemented in different software packages, making simultaneous simulations difficult to achieve, since communication typically requires file transfer from upstream to downstream. Moreover, the flow of information about the downstream state to the upstream models, which is necessary for an integrated control action is even more complicated or even impossible. Second, the state-of-the-art models use different variables to describe the aquatic system (e.g. BOD, COD, TOC, ... to describe organic pollution). Third, the hydraulic equations, which describe flow propagation in sewer pipes and rivers (the "de Saint-Venant" equations) are non-linear partial differential equations. These require complex numerical algorithms to solve, making the models slow and thus difficult to use for optimisation studies.

The first problem of the different software packages was solved by implementing all models in the WEST® simulation software. One of the key features of WEST is its possibility

to integrate multiple processes. To enable this coupling, a powerful model base structure was developed. This model base is aimed at maximal reuse of existing knowledge and is therefore structured hierarchically. The original model base for WWTPs was reorganised and extended to incorporate models of the sewer system and rivers. Moreover, a general concept to connect models with different state variables was developed. In these connectors logical transformations of state variables are incorporated, while also the mass and elemental balances are closed by using correction terms.

The calculation time of the integrated model is reduced by applying two concepts: model simplifications with mechanistic surrogate models and model reduction. Model simplification mainly focuses on replacing complex equations or concepts with more conceptual ones. The complex mechanistic models which are known to have a good predicting capability (if calibrated correctly) are used to generate data by virtual experiments transferring the knowledge compiled in their equations to the surrogate model. In this way, the mechanistic surrogate model can be calibrated on the basis of more data than could be collected by field measurements. This concept was applied to both the WWTP and the river system. Model reduction focuses on the elimination of parts of the model that are not influenced by the control strategy under study. In this way, upstream and downstream parts may be eliminated together with some conversion models. A last reduction focused on obtaining a shorter time period that had to be simulated for the optimisation of the control strategy.

In chapter 5, it was tried to replace the known ASM2d model (Henze *et al.*, 2000), by a grey box model. In this grey box, the mass balance was incorporated, while the conversion term was predicted by an artificial neural network (ANN). This concept was first tested on a simple conversion model with one type of substrate and one type of biomass converting this substrate. A neural network could be trained to reasonably predict the conversion rate one step ahead. However, due to the feedback of errors back into the model, long term predictions of the reactor could not be obtained. Therefore, an alternative approach to the reduction of the ASM2d and Takács settler model (Takács *et al.*, 1991) was followed. In this case, four different reductions were tested. The simulation results of the reduced models were compared to the complete model by looking at different properties of the effluent time series, such as average or maximum concentration, frequency distribution, plots, etc. It was concluded that it is not straightforward to decide whether two effluent series are sufficiently close to legitimate the use of the reduced model.

The equations within the modelling of the IUWS with a big impact on the calculation time are the “de Saint-Venant” equations. These equations were replaced by the concept of Continuously Stirred Tank Reactor (CSTRs)-in-series. The possibilities to calibrate such a CSTRs-in-series model to the data generated by a complex model were tested in chapter 6. An adapted geometry concept was necessary to obtain a reasonable description of the river geometry. With this concept, an equation with three hydraulic parameters could be calibrated to describe the flow-depth relationship for every river stretch. When connecting the different tanks, both the flood wave and pollution wave could be approximated sufficiently close to allow the use of this model within an IUWS model.

In a next part, a case study on the Lambro catchment (Italy) was used to test the capabilities of the integrated modelling approach chosen. The main goal of the study was to predict the immission concentration of LAS, a detergent with a good biodegradability. A model of the WWTP and a model of the river were constructed separately using the data available. These data however, were not sufficient to allow for a detailed calibration of the system. However, for the WWTP a reasonable approximation of the observed behaviour could be obtained. The hydraulic properties of the river Lambro were approximated by using 47 tanks in series, using the measured boron concentrations as tracer data for the calibration. In a next step, the in-stream degradation constant was estimated. With this integrated model, the impact of a bypass and the effluent of the treatment plant on the immission concentrations of LAS were evaluated. In a last phase, the effect of an upgrade of the treatment plant on the LAS concentrations was evaluated.

In a last part of the thesis, an integrated model of the catchment of Tielt was constructed. With this model, an immission based control strategy was designed and optimised. This control strategy focused on minimising the maximum ammonia concentration in the river. For the sewer system, the Kosim model was used, which was calibrated on the basis of a complex model. This Kosim model could be reduced from 68 elements to 4 elements, since only the last four elements were important for the control strategy. For the river, no complex model was available and, therefore, a CSTRs-in-series model was constructed directly. For the tuning of the control strategy, no conversion model was used in the river. In a first strategy the WWTP was overloaded when the immission concentration of ammonia in the river reached a given threshold. In a second strategy, the first strategy was extended by the implementation of an extra pump in the sewer system. In this way, more water could be sent to the WWTP, with a reduction of the CSO volume as a consequence. Both strategies could reduce the ammonia concentration in the river in certain parts of the storms studied.

As a secondary objective for the control strategies the minimum oxygen concentrations in the river were checked. Only the river model was used, but a submodel of the RWQM1 model (Reichert *et al.*, 2001b) was used as a bioconversion model. It could be concluded that the control strategies did not have an inverse impact on the oxygen concentrations in the river. In a last phase, the robustness of the control strategies towards changes in the system properties was tested. Three properties were changed: the aeration capacity, the nitrification capacity and the nitrogen load. The control strategies had about the same robustness as the reference case for the maximum ammonia concentration. This means that the control strategy will, if implemented in practice, perform still reasonably well under different conditions.

In a last chapter, an predictor for the minimum oxygen concentration in the river was developed and used in a immission based control strategy. The effect on the oxygen concentration in the river was small. Moreover, the measurement problems of OUR in practice will decrease the performance of the controller. The concept of using software sensors in immission based control strategies was demonstrated to be an interesting approach.

Overall, in this thesis, a procedure to create an integrated simultaneously simulating model of the IUWS system has been outlined. This model can be used to design and tune immission based control strategies. These strategies are shown to be a valid option in urban wastewater management driven by receiving water objectives. However, some problems remain to be solved such a data collection for large basins, calculation times of basin-wide models, knowledge about the phenomena (e.g. ecology), conservatism of the management, etc.