Model reduction through boundary relocation to facilitate real-time control optimisation in the integrated urban wastewater system

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Abstract Real time control is one of the possibilities to minimise the impact of the integrated urban wastewater system (sewer system and treatment plant) on the receiving water quality. Integrated control uses information about the river state to act in the sewer system or in treatment plant. In order to test and tune these integrated controllers, a simplified integrated model is needed. Even with these simplified models, the simulation times may be too long and further model reduction is needed.

In this paper, dependency-structure based model reduction is proposed as a technique to further reduce model complexity. Three steps are proposed: relocation of the upstream system boundaries to just upstream of the first control point, relocation of the downstream boundaries to just downstream of the last measurement point, and third, a further model simplification based on an analysis of the sensitivity of the control actions on submodel elimination. The effect of applying the different reduction approaches on the control strategy and on the resulting river water quality is discussed on the basis of a case study of the catchment of Tielt.

Keywords Integrated urban wastewater system; model reduction; real time control

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Introduction

The urban wastewater system (sewer system and wastewater treatment plant) has a major impact on the water quality of the receiving water (urban rivers or lakes). During rain events, the sewer system might spill diluted, but untreated water in the receiving water via combined sewer overflows. The wastewater treatment plant on the other hand, continuously discharges effluent which contains, depending on the treatment efficiency of the plant, more or less pollutants. The effluent always contains some pollutants and has consequently an impact that is probably not negligible. In order to optimise river water quality, a control strategy which exploits the interactions between the different subsystems and has as a final goal to optimise the receiving water concentrations, was shown to be a very promising option (Bauwens *et al.*, 1996; Rauch and Harremoës, 1999; Meirlaen *et al.*, 2002).

In order to tune such a control strategy, an integrated model of the system is necessary. One of the problems currently encountered is the fact that the simulation times are too long to optimise a control strategy. A possible solution is to use simplified models for each of the subsystems. An alternative or complementary approach, is the one proposed in this paper, to eliminate parts of the model which are not influenced by the tested control strategies. In this paper, first a description of the catchment is given, together with the models and control strategies used. In the next section, the general approach about the model reduction techniques is outlined. Finally some simulation results are shown, to illustrate the effect of the integrated control strategy on the water quality.

Materials and methods

Catchment description

The catchment under study is part of the catchment of the town of Tielt. This catchment has been described in previous studies as part of European TTP projects (Van Assel and

Dierickx, 2000). Two watercourses drain the catchment, the Poekebeek and the Speibeek. The main sewer system is a fully combined system and serves the area of the town of Tielt and some surrounding villages. It has a branched structure, with the different branches ending in a large collector which transports the water towards the treatment plant. Combined sewer overflows are present on both watercourses, while the effluent of the treatment plant is discharged towards the Speibeek. To judge the effect of the interaction between the sewer system, treatment plant and the river, the Speibeek was chosen as the river to be optimised in terms of river water quality, without altering the water quality of the Poekebeek. The river water quality has been judged according to a simple, though very important criterion, the maximum ammonia concentration in the river along the reach under study, while the oxygen was considered afterwards. Four important overflows are present on the Speibeek. The base flow of the Speibeek is very low, and has been assumed to be 10 l/s during the period under study. In fact, the overflow Deinsesteenweg acts as the main source of flow during rain events. As schematic overview of the modelled part of the catchment is given in Figure 1.

Model description

In order to work out an integrated control strategy, an integrated simultaneously simulating model of the complete system is a necessary tool. Once such a model is created, with all the problems associated with it (Meirlaen *et al.*, 2001), it might be used within optimisation studies. For these studies to be feasible, simulations should be the least time consuming possible. Therefore, the "de Saint-Venant equations", which describe flow propagation in sewer pipes and open channels, have been left out in the modelling approach adapted by Meirlaen *et al.* (2001). They have been replaced by a tanks in series approach (i) to describe flood wave propagation and dispersion phenomena in rivers (Beck and Young, 1975), and (ii) to describe surface run-off and in-sewer flow, in a similar way as done in the Kosim model (Paulsen, 1986).

Sewer model. The sewer system has been modelled with Hydroworks (Wallingford Software, UK) and calibrated on the basis of several measurement campaigns. Subsequently, a simplified Kosim model was constructed on the basis of this detailed model. It was found that total overflow volumes and overflow peak discharges were

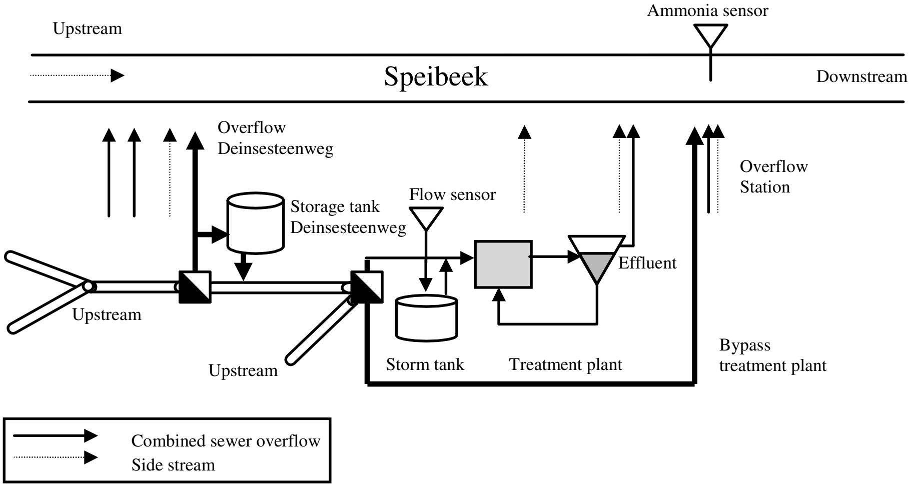

Figure 1 Overview of the discharges located along the Speibeek

modelled with the same accuracy in both types of models. (Van Assel and Dierickx, 2000). No biological reactions were taken into account in this simplified model.

Treatment plant model. The treatment plant of Tielt is an extended aeration plant with biological phosphorus removal. It has been modelled using the ASM2d model (Henze *et al.*, 2000) for the activated sludge part, while the settling model of Takàcs *et al.* (1991) was used to describe the behaviour of the clarifier. Intensive measurement campaigns have been carried out to allow the calibration of the most important parameters (Carrette *et al.*, 2001).

River model. The river model is built as a series of completely stirred tank reactors (CSTRs) to describe the hydraulic routing of the river, while a submodel of the RWQM1 (Reichert *et al.*, 2001) has been used to describe the biological conversions in the model. The most important differences with the full RWQM1 are the one-step nitrification process with one type of nitrifying biomass, while no algae or consumers were taken into account. Since very few data were available about the water quality of this small river, this model should be considered a hypothetical model, which can however be used to evaluate the impact of the different control strategies.

Control strategy description

Reference control strategy. The reference control strategy is acting on the stormtank at the treatment plant. If the incoming flow at the plant is higher than the design capacity (3DWF), the flow is redirected to the stormtank. Once this tank is filled, the water is bypassed and spills 2 km downstream of the plant at the overflow station. The aeration of the biological tanks is controlled by local time based controllers.

Control strategy 1. This control strategy focuses on the elimination of peak ammonia concentration in the river downstream of the treatment plant. For this, an ammonia sensor has been placed into the river at the point where the highest concentrations of ammonia occur, this is at the overflow station. The overloading of the treatment plant is controlled on the basis of the ammonia measurement in the river with a proportional controller with a maximum value. This means that the inflow to the treatment plant is proportional to the difference between the ammonia concentration in the river and a given set point. The proportional constant was chosen in such a way that the maximum overloading of the plant (4 DWF) was reached if this difference was 1 mg NH_4-N/l. Since the sludge retention time in the settler is less than one hour, no important release of ammonia is expected in the secondary clarifier. The overloading of the treatment plant is only activated when the stormtank is completely filled. Moreover a supervisory controller on the sludge blanket was implemented to prevent massive sludge wash-out. If there is any risk of sludge loss via the settler (defined as the sludge blanket reaching a certain height) the flow is restricted again to 3 DWF. More details about the construction of the submodel and the used control strategies can be found in Meirlaen *et al.* (2002).

Control strategy 2. Control strategy 2 extends control strategy 1 in order to optimise the operation of the sewer system. It was noticed that the hydraulic capacity of the connection between the storage tank at the Deinsesteenweg and the overflow station was only completely used when the storage tank was completely filled. This is due to the flow being dependent on the head of water in the tank. By adding a pump to this system, the downstream flow is no longer dependent on the water head in the tank, and the hydraulic capacity of the pipe could be completely used, even before the tank is completely filled. In this way more water can be sent to the treatment plant in the beginning of an event, while at the end of an event the storage tank can be emptied faster. The pump is only active when the treatment plant is not hydraulically overloaded. An extra control option was added to directly spill the wastewater at the overflow Deinsesteenweg when the water was very diluted.

A summary of the different control strategies is shown in Table 1.

Results and discussion

Dependency-structure based model reduction

The problem with integrated models is that, despite the choice for already simplified – surrogate – models, they still do not allow sufficiently fast calculations to easily perform control optimisation studies. Therefore, further model reduction and acceleration possibilities are developed in this work, however with minimal deterioration of the accuracy with which the performance of the proposed control strategies can be evaluated. Three approaches are investigated to create a so-called control model that can be used to design, optimise and tune a control strategy:

- Relocating the upstream system boundaries of the controlled system to those points just upstream of the most upstream control action.
- Relocating the downstream system boundaries on the basis of the location of the most downstream sensors used in the control strategy.
- Reducing model complexity further on the basis of an analysis of the sensitivity of the control actions on submodel elimination.

The first acceleration focuses on the fact that in both the sewer system and the river system under study, relatively large parts of the system are located upstream of the most upstream control action. This means that, whatever the control action is, the model output for these parts will always be identical. Hence, it is not necessary to recalculate these parts in the optimisation study. The system boundaries for the controlled system can be relocated and influent files might be generated at these new system boundaries. It is important to notice that they only have to be generated once and can be reused afterwards for all control system evaluations. Consequently, important timesavings can be achieved. To a certain extent this relocation of the system boundaries can be automated by using the dependency structure between the model variables that is constructed during model analysis (Vangheluwe *et al.*, 1998).

A second reduction focuses on the fact that it may not be necessary to calculate all conversions occurring in the downstream part of the receiving water very accurately since the inclusion of these conversions would not have an impact on the way the controller calculates its control actions. For instance, when the controller aims at minimising the peak ammonia concentration in the river, one can imagine that this concentration most probably occurs at those locations where either sewer overflow or treatment plant effluent are mixed with the receiving water. For this example, two things can be taken advantage of. First, there is no time delay (assuming immediate mixing) between the discharge of the pollutant

Table 1 Summary of the three control strategies tested

Name	Description
Reference control strategy	Local control of the stormtank, local aeration control
Control strategy 1	Reference control + integrated control on the overloading of the TP based on the ammonia measurement in the river and supervised by the sludge blanket height
Control strategy 2	Strategy 1 + pump in the sewer system, pumping more water downstream when the storage tank at Deinsesteenweg is not completely filled and the TP is not overloaded + possibility to spill directly if the water is very clean in terms of ammonia

and the effect in the river and, hence, a measurement of ammonia at the mixing point can be considered sufficient as an input to calculate the control actions more upstream in the system. This is in contrast with a situation where one, for instance, focuses on the minimum oxygen concentration in the river, which will be located at quite a large distance downstream of the place of discharge since the oxygen consumption may take considerable time. Moreover, the location of the highest peak of ammonia has a fixed location (the critical mixing point) and can, hence, be measured with an ammonia sensor located at that site. When looking at the minimum oxygen concentration, however, the place where the minimum occurs will depend on a lot of factors such as the flow rate, biomass concentration in the river, biodegradability of the organic pollution, etc. In conclusion, for simulation of an ammonia controller it is sufficient to model a system ending at the critical mixing point where the ammonia sensor is located. Hence, the downstream part of the river does not have to be taken into account to calculate the control actions with the control algorithm.

Third, to support a further reduction of the model complexity, it can be evaluated whether the control actions are sensitive to the elimination of a certain submodel in the overall model. This is basically a more concrete application of the ideas presented by Rauch *et al.* (1998) concerning the fact that in most cases the purpose of water quality management does not need to consider all aspects of the river system. Other hints on submodel selection are given in Vanrolleghem *et al.* (2001). One could, for instance, replace the two step nitrification process by a one step process, and ignore the influence of algae and consumers.

The different steps of these model reductions are shown in Figure 2. The upstream parts of the sewer system may be eliminated since the control actions can never influence the behaviour of those parts. The upstream river part may be eliminated since no flows controlled by the control strategy enter this part of the river. The downstream part of the river may be eliminated since the ammonia criterion is most critical at the last discharge point. Further on, conversion processes might be left out of the river model, only retaining the transport part.

As a last point to the model reduction, it might be useful to relocate the time bounderies of the system. If the period under study contains a dry period at the start, to control options won't have any influence until the first rain event occurs. Therefore, one could simulate the first dry period only once to get a kind of steady state in dry conditions and start with the control simulations a short time before the first rain event. It is also possible to cut off the last part of the simulation, although one cannot stop directly after the last rain event, since

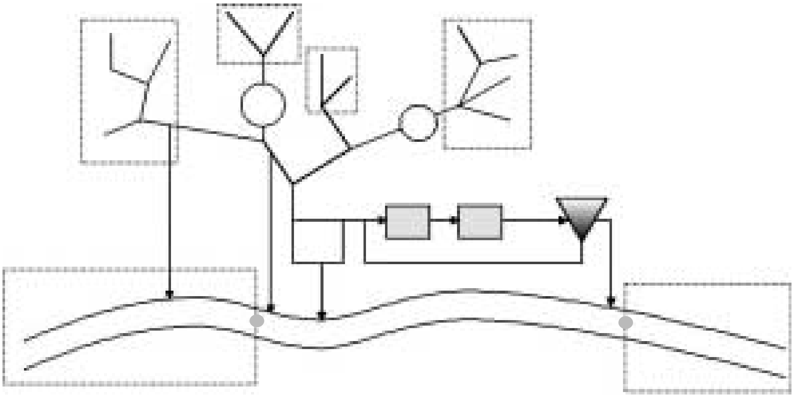

Figure 2 The model of the integrated urban wastewater system with location of sensors (closed circles) and control actions (open circles). The parts that can be eliminated to construct the control model are indicated with dashed boxes

one has to be sure that the effect on the receiving water has completely been calculated before ending the simulation.

Secondary objective evaluation

In the example used in the study we have tried to maximise the model reduction via system boundary relocation and submodel selection, leading to a so-called control model. We only focused on the peak ammonia concentration and this allowed us to eliminate for instance the section of the river downstream of the ammonia sensor. However, in river water quality management some secondary objectives are typically formulated as well, for instance the already mentioned minimum oxygen concentration. Hence, although for calculation of the control actions no downstream information is necessary, the strategy itself should be evaluated in terms of its performance with respect to the secondary objectives.

By doing so, the full effect of the control strategy on the river system is verified, and some proposed control strategies might be rejected completely on the basis of the results of this secondary objective evaluation and sensitivity analysis. Less severe than a complete rejection, the results may also suggest a further optimisation of the control strategy's characteristics (set points, tuning parameters) with the full model. The advantage is of course that these characteristics have already been given values that are probably close to the optimum for the complete model.

Model reductions applied on the Tielt case study

The Kosim model of the complete catchment of Tielt consists of 68 elements. Since the most important overflows are located close to the treatment plant (both the overflow at Deinsesteenweg and at the station), only four elements had to be retained in the control model. These were the CSO structure at Deinsesteenweg, the storage tank at Deinsesteenweg, the pipe between these structures and the overflow at the station, and the overflow structure at the station itself. This resulted in a substantial model simplification and only this part of the sewer model has been implemented into WEST® (Hemmis, Kortijk, Belgium). The upstream parts of the sewer model were calculated once and used as an input file for the simulation. This is a clear example of system boundary relocation.

For the treatment plant model simplifications, several options were tried out. The first idea was to replace the deterministic model by a neural network. This approach did not work, mainly due to the feedback of errors into model, leading to an accumulated error and no useful results (Meirlaen and Vanrolleghem, 1999). First the model described by Takàcs was replaced by a conceptual model. In this model, a fraction of the incoming solids was directed towards the effluent, while the remaining part was concentrated in the return/waste sludge. Secondly, the oxygen dynamics were taken out of the activated sludge tanks, assuming either no oxygen in the non-aerated case and no limitation of the biomass by oxygen in the aerated case. In this way a fast process was eliminated from the model. However, since the control strategy allows some hydraulics overloading of the plant, both the oxygen dynamics and the behaviour of the sludge blanket were considered to be important processes during storm events. Therefore, the proposed model reductions of the treatment plant model could not be used in order to be able to realistically describe the behaviour of the treatment plant during storm conditions.

The complete river model of the Speibeek used to evaluate the effect on the oxygen dynamics has 18 tanks in series. Leaving out the part of the model upstream of the first controlled overflow (at Deinsesteenweg) and the part of the model describing the part downstream of the overflow at the station resulted in a control model of only six tanks. After this relocation of the boundaries of the system, the sensitivity of the control model towards the elimination of the conversion model was checked. In the studied example, the nitrogen discharged from a sewer system is already ammonified to a large extent and, therefore, the ammonia concentrations in the wastewater might be rather high compared to the total nitrogen content. When focusing on controlling the peak ammonia concentration, it might therefore be sufficient to only look at the transport of ammonia, and to neglect the conversions taking place in the river (like ammonification or nitrification). In this way, by eliminating the river conversion model from the mass balances, only retaining the transport term, simulation time, and hence optimisation time will be saved.

Since the first important rainstorm occurs during the 7th day, a relocation of the time boundaries could also be achieved. Since the controllers do not act in either of the cases before the end of the sixth day, the behaviour of the models is independent on the selected control strategy. Therefore, one simulation was performed to determine the state of system at the beginning of the seventh day, and all other simulations were run starting from that time and with the initial conditions being determined by this simulation.

Simulation results

A two week period with no major storms had been selected from the available data to test the control strategies. Since system boundary relocation has no influence on the model results, only the effect of the elimination of the conversion model had to be checked against the results obtained when the conversion model is taken into account.

Some simulation results are shown in Figure 3. It can be seen that the effluent concentrations of the treatment plant are not changing very much, even though the plant is overloaded during certain periods. In the reference control case, the inflow goes up to 3 DWF, while in control strategy 2 the maximum overload factor is 4 DWF. Since the treatment plant is an extended aeration system, sufficient nitrification capacity is available, while no problems with the settling are also to be expected, even during high hydraulic loading.

In Figure 4, the effect of the control strategy can clearly be seen, since the ammonium concentration is always lower than or equal to the concentration in the reference control case. However, the effect is not always caused by the same mechanism. In the first part of each storm (from day 6.5–6.7 and 7.1–7.3), the storage tank at the Deinsesteenweg, is not completely filled and hence the flowrate of water to the treatment plant is not maximised in the reference control case. By adding a pump, more water can be send downstream even without the tank being completely filled. The additional water which is sent downstream, saves some space in the storage tank, which can be used later on to store polluted water. However, due to the limited capacity of the pipe downstream of the storage tank at the Deinsesteenweg, not all of the combined sewer overflow can be avoided, leading to increased ammonia concentrations in the river. If the hydraulic capacity would be bigger, a more substantial reduction in ammonia concentration can be expected.

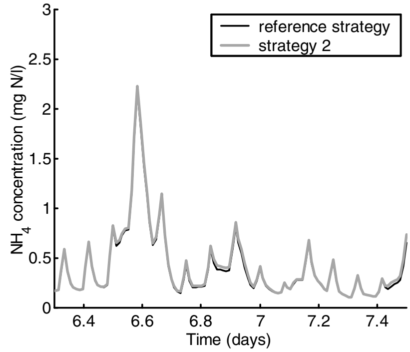

Figure 3 The resulting effluent ammonia concentration in both the reference control case and control strategy 2

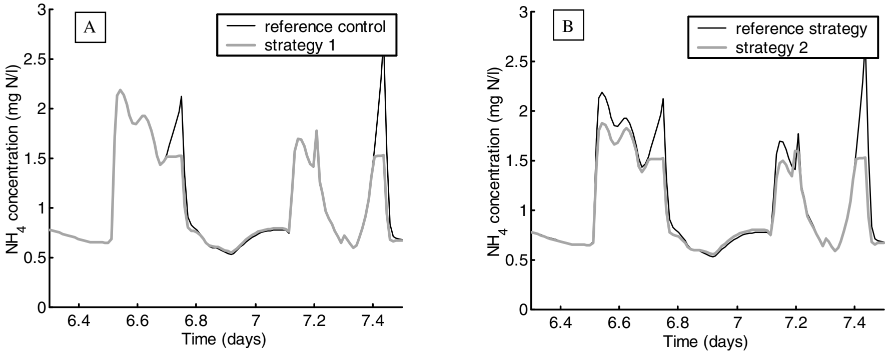

Figure 4 Simulated ammonia concentrations at the overflow station. Comparison between the reference control strategy and strategy 1 (left) and strategy 2 (right)

In the second part of the evaluated storms (6.7–6.8 and 7.3–7.5), the stormtank is filled in both cases, so the addition of the pump does not have any effect any more on the resulting flow. However, in this case the overloading of the treatment plant starts to act in the first and the second control strategy. This overloading is only activated if the ammonia concentration in the river at the discharge point is above a given set point, which was chosen 1.5 mg NH_4-N/l in this case. The overload factor was proportional to the difference between the set point of ammonia in the river and the actual measured concentration. It can be seen that in the second part of the selected rain events, the ammonia concentration can be controlled to this set point. This effect on the ammonia concentrations in the river could clearly be noticed from the difference in the simulation results between the control strategy 1 and 2. In the first case, an improvement was only noticed in the second part of the storm (Figure 4A), while in the second case, both parts of the storm showed an improvement (Figure 4B). However, there is not sufficient control authourity to control completely the first peak, but still an improvement can be seen in the first part of the storms.

Conclusions

The overall procedure is then as follows. First, construct a reduced model (the control model) using system boundary relocation and submodel selection to allow efficient design, optimisation and tuning of the control strategy. After determining the optimal set points and parameters of the control laws via numerical optimisations with this control model, a different set of simulations is done with a more complete model with two aims: evaluate the secondary objectives, and evaluate whether control performance is sensitive to the selection of a conversion submodel. In this way the control strategy can be checked against a more detailed and hence accurate model. Based on these simulations, the control strategy can be adopted, adapted or even rejected.

This reduction technique was used in a case study on the catchment of Tielt. For the selected rain events, it was shown that a substantial reduction in model complexity could be obtained by still keeping sufficient accuracy for the defined goals. By choosing ammonia as a primary control variable, the downstream part of the river could be eliminated from the control model, resulting in a river model consisting out of six tanks in series rather than 18. As a first improvement the measurement of ammonia in the river was used to decide on the overloading of the treatment plant. In a second option, a pump was installed in the sewer system, leading to an increased flow towards the treatment plant, and hence in a reduction in combined sewer overflow volume. The simulation results for the oxygen concentration were checked already in the first option and showed an improvement in the oxygen dynamics of the river. It is expected that this will also be the case in the second option (integrated control with pump).

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