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Modelling and real-time control of the integrated urban wastewater system

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Abstract

In the European Union, the Water Framework Directive (WFD) enforces a good ecological and chemical status of all surface waters. In-stream (immission) concentrations and populations need to comply with certain standards. In order to deal with this new legislation, integrated urban water management is an important issue. Real-time control (RTC) is one approach that may be used to improve the performance of the system. Immission-based RTC has been suggested as a proper instrument to help fulfilling the WFD requirements. In order to design and tune an immission-based RTC scheme and to judge the overall effect on the receiving water, an integrated mathematical model of the urban wastewater system is necessary. Several problems are encountered when creating such a model and solutions are discussed in this paper. With this integrated model, an immission-based control strategy is developed for a particular case study and is shown to be able to improve the water quality compared to the uncontrolled case. In the final part, the robustness of this control strategy is tested, as an important additional measure of performance. It can be concluded that there are tools available to help dealing with the operational consequences of the WFD.

Keywords: Immission; Integrated urban wastewater system; Model reduction; Real-time control; Receiving water

1. Introduction

The integrated urban wastewater system (sewers and treatment plants) has a major impact on the quality of the receiving water, due to discharges of combined sewer overflows (CSO) during storms and due to the effluents of the treatment plants.

When trying to protect the receiving water from dramatic impacts, both the US and the EU have developed important, advanced regulation. The US Clean Water Act establishes a process to facilitate recovery of surface waters not meeting their established water quality standards. It is the responsibility of the state and/or federal agencies to develop an appropriate total maximum daily load (TMDL) for each water body and for each identified pollutant. The TMDL identifies the amount of pollutant loading that a water body can receive and still provide its designated uses (like drinking water production, recreation,…) (Havens and Schelske, 2001).

In 2000, the Water Framework Directive (WFD) (Council of the European Communities, 2000), was adopted in the EU, which complements previous directives. The main objectives of the WFD are (Blöch, 2001):

- integrated river basin management across borders, with coordinated programmes of measures,
- protection of all waters, surface waters and groundwater, in quality and quantity with a proper ecological dimension,
- emissions and discharges controlled by a "combined approach" of emission limit values and quality standards, plus the phasing out of particularly hazardous substances,
- introducing water pricing policies,
- strengthening public participation.

For surface waters the objective is that of a "good" ecological and chemical quality status. A surface water is defined of good ecological quality if there is only slight departure from the biological community that would be

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expected in conditions of minimal anthropogenic impact. These expected conditions might differ from member state to member state (Kallis and Butler, 2001). Quality elements for assessment are divided into biological elements (e.g. composition and abundance of flora and fauna), hydromorphological elements (e.g. quantity and dynamics of flow, river depth and width variation) and supporting physico-chemical elements (e.g. thermal/oxygenation conditions, salinity, nutrients, etc.). Chemical status is classified only into two categories: "good" and "failing to achieve good". A "good" water body fulfils all the standards set by EU legislation, for the concentration of chemicals in water.

The WFD mentions explicitly that ecological integrity is an important goal. This has important consequences for the current practices in integrated urban water management. Traditional engineering solutions like minimizing CSO volumes are no longer sufficient, since they do not guarantee that the good ecological status will be met (Butler and Schütze, 2005). Therefore, new techniques and models will have to be applied in order to perform a system analysis which allows these advanced goals to be met (like immission-based control, uncertainty analysis, ecological modelling). So far, most models have been dealing with the emissions from the sewer system and the treatment plant separately, while currently more research is being devoted to the resulting "immission concentrations". However, ecological modelling and predictions of ecosystems behaviour are still a problematic issue, although advances are being made (Schleiter et al., 1999; Goethals and De Pauw, 2001). In this respect, also a wider perspective should be adopted considering the fundamental distinction between engineering and ecological resilience and the time scale of disturbances (Beck, 2005).

It is clear that many factors influence the quality of receiving water like urban wastewater, industrial wastewater and non-point agricultural sources, which require particular tools from a watershed modelling perspective (Rousseau et al., in press). In highly urbanized regions like Flanders (Belgium), the impact of the urban wastewater system is very important for a number of small rivers which drain the cities. The current Flemish legislation allows CSOs to spill seven times a year. As a consequence large CSOs spill into these small rivers with little dilution capacity, turning the river water into diluted sewage with a very low quality. As a consequence of these regular spills, the ecological status of these rivers deteriorates to unacceptably low levels (Wils, 2000).

To minimize this impact in a given situation, several approaches can be used. One can, for instance, build extra storage volume or put bigger sewer pipes into the ground. Usually this type of solution is very expensive and is only feasible if sufficient space is available. Another option is the use of real-time control on the existing sewer system and/or treatment plant. Typically this type of solution requires less investment costs and tries to make optimal use of the facilities already present in the catchment (Schilling, 1989). An overview of the status of RTC in urban drainage today is given by Schütze et al. (2002b).

Mathematical models are useful in the design and tuning of such control strategies, since the possibilities to evaluate a strategy in practice are usually very limited. When using a mathematical model of the system under study, different sensors (level, flow, DO, ammonia, pH) and/or actuators (pumps, weirs) can be selected and evaluated before investing in expensive equipment. Moreover, different control laws can be easily tried and the parameters of the selected control law can be tuned without risk of disturbing the system. Common control laws generate an action of the actuator that can be proportional to the error (difference between the measurement and the set point of the variable) like in P controllers, proportional both to the error and to the integral of the error (PI controllers), or based on qualitative descriptions of the process variables (fuzzy controllers).

Different types of real-time control can be distinguished: volume-based RTC, pollution-based RTC and immission-based RTC. In volume-based real-time control, the control strategy is designed to minimize the volume of polluted water entering the receiving water by storing or treating it. This approach is successfully applied for instance by Pleau et al. (2001, 2005). Pollution-based real-time control tries to minimize the total amount of pollutants entering the receiving water by preferably storing polluted water and spilling more diluted water (Weinreich et al., 1997). Finally, immission-based real-time control tries to optimize the receiving water quality directly. This means that sensors in the receiving water are used to manipulate pumps and weirs in the sewer system, treatment plant and/or receiving water (Erbe et al., 2002).

Real-time control can be applied on the sewer system, on the treatment plants or on the receiving water (Reda, 1996). The objectives of these control strategies are e.g. to minimize the total overflow volume or to avoid sludge washout during hydraulic overloading of the plant. Different studies show the beneficial effect of these control actions (among others, Nielsen et al., 1996; Entem et al., 1998; Petruck et al., 1998). However, Rauch and Harremoës (1999) showed that minimizing the total overflow volume not necessarily results in the best water quality possible. It therefore seems necessary to take into account the resulting river water quality when determining the control actions, rather than starting from the traditional emission point of view. In order to optimize river water quality, a control strategy which exploits the interactions between the different subsystems and with final goal to optimize the receiving water concentrations, was shown to be a very promising option (Bauwens et al., 1996; Rauch and Harremoës, 1999; Schütze et al., 2002a).

Immission-based real-time control takes the resulting river water quality directly into account. For the development of such control strategies an integrated model with the three subsystems running simultaneously is essential. Indeed, with a simultaneous simulation, the current (and predicted) states of the river water can be used to determine the control actions in e.g. the sewer system. In sequential simulation on the contrary this is not possible since the water quality is only calculated after the simulation of the other systems is completed. An integrated model can also be used when designing or upgrading a system, where it allows to quickly quantify the effect of different design options on the resulting water quality. Because of these advantages, a simultaneous simulation of the integrated urban wastewater system has been asked for since the last few years (Rauch et al., 1998; Schütze et al., 1999; Meirlaen et al., 2001).

In principle, RTC can be applied successfully to dry weather conditions as well, with different strategies and rules than in wet weather conditions, improving the performance of the system by equalizing loads and taking actions in case of failures or toxic spills in sewers, for example.

This paper is organized as follows. In the first part, the general approach towards modelling of the integrated urban wastewater system for real-time control development is explained. Two main ideas are presented to gain calculation time: model simplifications with mechanistic surrogate models and model reduction. After this introduction of the general approach, the Tielt case study is described, together with the model simplifications and model reductions applied. This results in a so-called "control model" which can be used for controller evaluation and optimization. Some simulation results are presented to show the effect of the implemented control strategies. Finally, the robustness of these control strategies against different system changes is tested and discussed.

2. Approach to modelling the integrated urban wastewater system

The urban wastewater system components (sewer, treatment plant and river) are often modelled using complex mechanistic models. For example, flow routing in sewer pipes or rivers is described by the 'de Saint-Venant' equations, which are based on the conservation of mass and momentum. These partial differential equations have to be solved using advanced numerical integration algorithms with a high computational burden, which makes the model impractical for use in long-term simulations or in optimization problems. However, this complex mechanistic model is able to accurately predict flood wave propagation in channels.

Design and tuning of control strategies are both examples of optimization problems which typically require a lot of simulations in order to find a (sub)optimal solution. Hence, shorter simulation times are required in order to find a solution within a reasonable time. Two solutions are proposed in this paper to decrease the simulation time during the optimization of the control strategies. The first is the use of mechanistic surrogate models. The second is model reduction through system and time boundary relocation.

2.1. Mechanistic surrogate models

The complex mechanistic models (with the "de Saint-Venant equations") as described above may be substituted by faster models. In this paper the term "surrogate" models is used for the latter, as they form a surrogate (an approximate substitute) for the "real thing", i.e. the complex mechanistic model that is approximating reality better. Surrogate models are faster, but are less but still sufficiently accurate.

The development of a mechanistic surrogate model requires a lot of data as most of the parameters in the model do not have physical meaning. Collecting all these data in measurement campaigns is an expensive and time-consuming task (Vanrolleghem et al., 1999), hence an alternative is proposed. The suggested procedure to go from reality to a surrogate model can be summarized as follows (a more elaborate explanation can be found in Meirlaen et al., 2001):

1. Determine the system under study, its boundaries and the problem to be solved.
2. Collect data on the system to calibrate a complex mechanistic model. This data collection may be assisted by optimal experimental design (OED) on reality by using the complex model to be calibrated.
3. Calibrate and validate the complex mechanistic model.
4. Generate data with the complex model to calibrate the mechanistic surrogate model. This data collection may be assisted by OED on the complex mechanistic model by using the mechanistic surrogate model to be calibrated.
5. Calibrate and validate the mechanistic surrogate model.

Fig. 1 shows the application of the very general concept on the urban wastewater system. Examples of this approach have been described before. Vaes and Berlamont (1999) used physically based conceptual models to assess combined sewer overflows. Fronteau and Bauwens (1999) compared the conceptual sewer model Kosim (Paulsen, 1986) with the complex mechanistic Hydroworks model (Wallingford Software, UK)

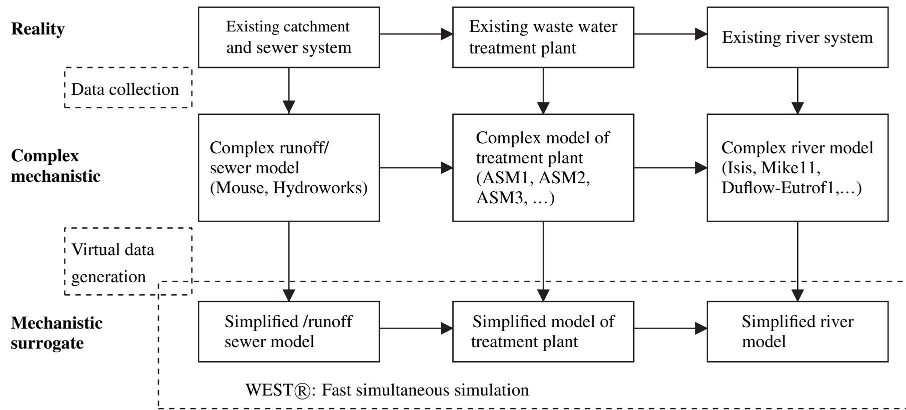

Fig. 1. The creation of mechanistic surrogate models in the urban water system.

with respect to their hydraulic description and the accuracy of CSO predictions. Long-term simulations gave similar results, but Kosim was significantly faster.

Flow routing in rivers can be approximated by a series of tanks with variable volume approach (Beck and Young, 1975). When these tanks are also used to describe the transport of solutes in the river, the model is also able to describe dispersion in a reasonably accurate way (Reda, 1996). When, in addition, a biological conversion model is used to predict the conversions taking place in the river, a series of continuously stirred tanks can be easily used for modelling the dynamics of river water quality. The procedure of calibrating the flow propagating properties of a series of tanks on data generated by the 'de Saint-Venant' equations was illustrated in a case study performed on the river Zwalm (Belgium) (Meirlaen et al., 2001).

2.2. Model reduction through boundary relocation

Model reduction with minimal deterioration of the accuracy is an additional way to develop a fast model. Four approaches are investigated to create a so-called control model that can be used to design, optimize and tune a control strategy (Meirlaen et al., 2002):

(1) Relocating the upstream system boundaries of the controlled system to those points just upstream of the most upstream control action.
(2) Relocating the downstream system boundaries on the basis of the location of the most downstream sensors used in the control strategy.
(3) Reducing model complexity further on the basis of an analysis of the sensitivity of the control actions.
(4) Relocating the time boundaries to exclude some periods at the beginning and the end of the optimization.

The different steps of these model reductions are conceptually presented in Fig. 2. The upstream parts of the sewer system may be eliminated since the control actions under study can never influence the behaviour of those parts. The upstream river part may be eliminated since no input influenced by the control strategy enters this part of the river. The part of the river

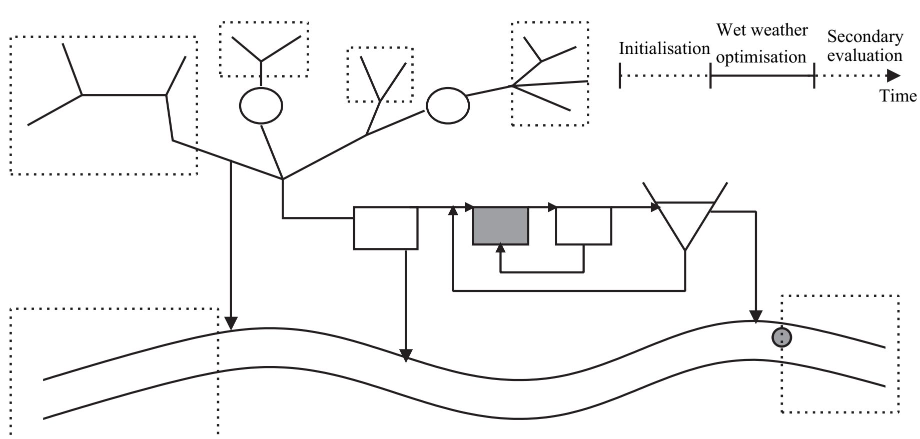

Fig. 2. The model of the integrated urban wastewater system with location of the sensors (closed circles) and control action (large open circles). The parts that can be eliminated to construct the control model are indicated with dashed boxes.

downstream of the last sensor may be eliminated since the control actions will not be affected by what happens there. Further on, conversion processes might be left out of the river control model, in case they do not influence the control actions. Also, the dry weather period at the beginning and at the end of the simulated period may be left out when tuning control strategies.

2.3. Secondary objectives evaluation

Any optimization study in environmental management is multi-criteria in nature, i.e. one has to take more than one objective into account when evaluating management or control strategies. Here, the objective(s) used as direct input to the controller is (are) termed the primary objective(s). These are typically the on-line measurements of the water quality variables that one wants to improve in a feedback control way. The secondary objectives, on the other hand, are all other objectives one is interested in, but which do not influence the controller directly. These might be unmeasured water quality variables, and also operating costs or operator acceptability (e.g. related to the complexity of the control system). With increasing stakeholder involvement, even public acceptability might become an issue (Cowie and Borrett, 2005; Fath and Beck, 2005).

Also the robustness of the controller is an important secondary objective. Here, robustness is defined as a measure of how well a controller works in situations which are different from those it was tuned for. This is in contrast with Pleau et al. (2005) where robustness is defined as the behaviour of the system in case of failure of certain elements in the control loop. When evaluating a control strategy, it would be of great interest to have a criterion that can indicate the range of application of the studied control strategy. In other words, it would be useful to have a measure of the sensitivity of the performance of the tuned strategy towards some system parameters. Vanrolleghem and Gillot (2002) proposed a global sensitivity analysis in which parameters that are uncertain or time-varying are evaluated. The relative sensitivity of the evaluated control strategies towards a system change for a given water quality criterion is calculated as follows:

$$S_i = \frac{\partial \text{criterion value}}{\partial \theta_i} \cdot \frac{\Delta \theta_i}{\text{criterion value}}$$

in which $\Delta\theta_i$ represents the range over which one can expect a parameter theta$_i$ to vary in the given system (Rousseau et al., 2001). The robustness index (RI) for a certain criterion then summarizes the sensitivities towards different system parameter changes

$$\mathrm{RI} = \frac{1}{\sqrt{(1/p)\sum_{i=1}^{p} S_i^2}}$$

where p is the number of parameter changes. If RI is large, the control strategy will perform more or less similarly in different conditions.

The tuning of a control strategy focuses on reaching the primary objective, for instance minimizes the peak ammonia concentration. Obviously, the actions generated by the control strategy also have an influence on the secondary objectives. It is therefore important to verify that the defined and tuned strategy, while improving on the primary objective, is not making things (a lot) worse on the secondary objectives. For instance, if the control strategy requires the addition of chemicals in the treatment plant, costs will have to be looked at. If, in another case, a storm tank needs to be built in a residential area, public acceptability might be a problem.

Compared to other studies (Rauch and Harremoës, 1999; Schütze et al., 2001; Butler and Schütze, 2005), the approach presented in this paper is based on the combination of complex and simplified models, while the study of truly integrated control has become possible here, thanks to the implementation of the simplified and reduced model within a single software package, WEST® (Hemmis NV, Kortrijk, Belgium; see Vanhooren et al., 2003). Hence, information about the state of the river can be used within the controllers acting on the sewer system and treatment plant.

3. The Tielt case study

3.1. Catchment description

The catchment under study is part of the catchment of the town of Tielt (Belgium, 20 km west of Gent). This catchment has been described in previous studies as part of European TTP projects (Van Assel, 2000b). Two watercourses drain the catchment, the Poekebeek and the Speibeek. An overview of the catchment is given in Fig. 3. The total area is about 11,000 ha, about 250 ha of which is impervious. The main sewer system is a fully combined system and serves the area of the town of Tielt and some surrounding villages. The total population is about 20,000 connected people, while also some industries are connected (5000 P.E. on flow basis). 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. The treatment plant of Tielt is an extended aeration plant with biological phosphorus removal. The plant has an

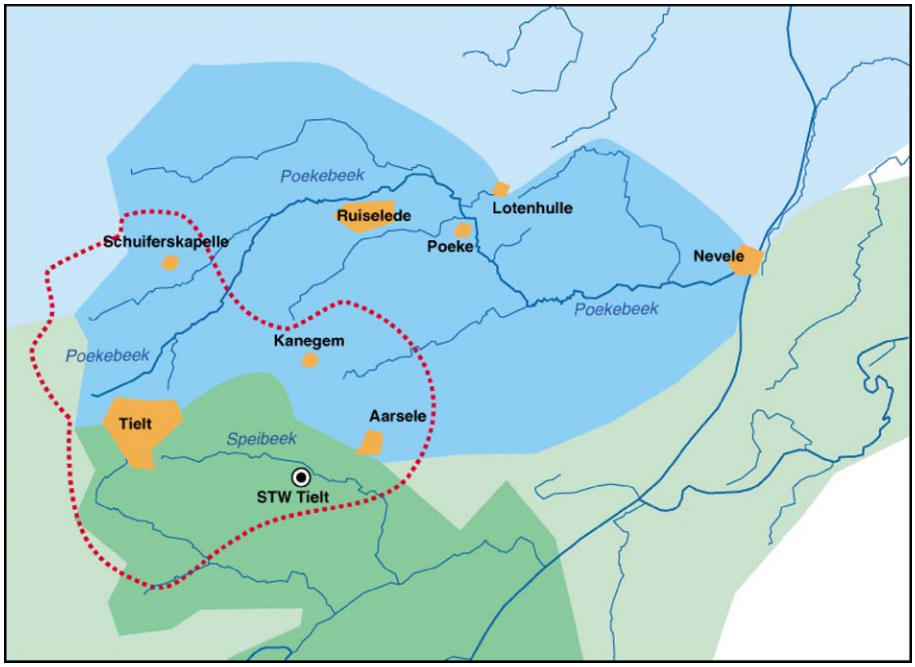

Fig. 3. An overview of the catchment of Tielt.

anaerobic tank (1000 m^3), two aeration basins (total volume of 5938 m^3), two secondary clarifiers (2152 m^3 each, diameter = 28 m) and a storm tank (also 2152 m^3). A schematic overview of the modelled part of the catchment is given in Fig. 4.

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 optimized in terms of river water quality. Care was taken not to alter the water quality of the Poekebeek to keep the comparison of approaches fair. 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 as a secondary objective. Four important overflows are present on the Speibeek, which is currently of bad quality in both dry and wet weather (e.g. 90% of the time oxygen concentrations are below 50% saturation). The base flow of the Speibeek is very low, and has been assumed to be 10 l/s during the period under study (i.e. summer period). This causes a very low dilution capacity which is typical for many small Flemish rivers. During this dry period, the impact of CSOs will probably be the most critical. In fact, the overflow Deinsesteenweg acts as the main source of flow during rain events.

3.2. Mechanistic model description

3.2.1. Sewer model

The sewer system has been modelled using Hydroworks (Wallingford Software, UK) and has been calibrated on the basis of several measurement campaigns. The model contains 1379 nodes, 22 outfalls,

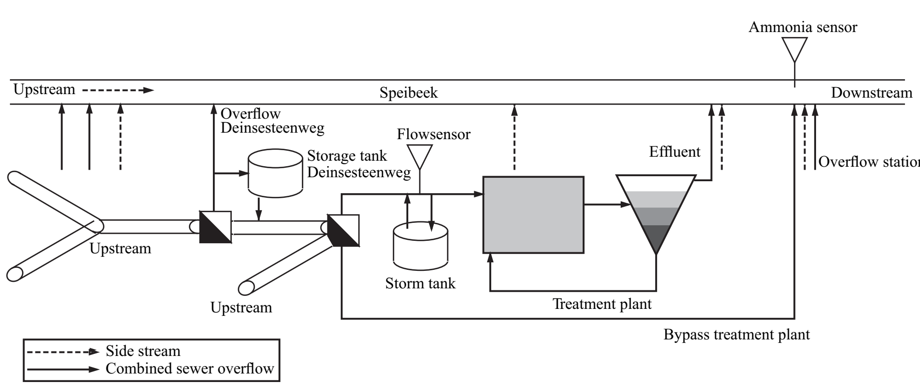

Fig. 4. Overview of the catchment under study at the Speibeek.

1381 conduits and 51 control links (Heip et al., 1997; Van Assel, 2000a). The model building has been performed in four consecutive steps: DWF and WWF hydraulic calibration and DWF and WWF water quality calibration. It was concluded that the model was calibrated correctly for the hydraulic part and performed reasonably well for water quality predictions under dry weather conditions. The wet weather quality predictions could not be evaluated in detail due to the too short sampling periods (Heip et al., 1997).

3.2.2. Treatment plant model

The treatment plant has been modelled using the ASM2d model (Henze et al., 2000) for the activated sludge conversion part, while the settling model of Takács 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). The influent fractionation (i.e. the division of the incoming COD in the state variables used in the ASM2d model) was the factor most influencing the predicted effluent quality.

3.2.3. River model

A complex mechanistic model was built for the Poekebeek system. Both hydrologic and hydraulic models were built and calibrated for flow simulation. Also, a river water quality model has been constructed. It was concluded that the flow could be simulated reasonably well, but that, due to software and data problems, the water quality dynamics could not be described properly. No complex mechanistic model of the river Speibeek was built, due to a lack of data.

3.3. Control strategy description

In this case study, the existing sewer system and treatment plant (designed to comply with the Flemish emission standards) are, with the current static operation, not able to ensure a good water quality in the Speibeek. To tackle this, immission-based control strategies are developed to evaluate whether the problem can be solved without rebuilding the sewer system, change the treatment plant or add large storage tanks. Two control strategies are compared to the current static control strategy. The first control strategy uses measurements in the river to act on the WWTP. The second strategy extends the first one, by also acting on the sewer system.

An efficient control strategy acting on both the sewer system and the treatment plant might improve the quality of the Speibeek, since the impact of the CSOs is very large due to the very low dilution capacity. Since this is a typical Flemish situation, the ideas presented below might be (in a modified format) applicable in other situations as well.

3.3.1. Reference control strategy

The reference (existing) control strategy is acting on the storm tank at the treatment plant. If the incoming flow at the plant is higher than the design capacity for biological treatment ($3Q_{14} = 23{,}000\ m^3$/day, where Q_{14} is the daily average DWF times the ratio 24/14), the flow exceeding this capacity is redirected to the storm tank. Once this tank is filled, the water that cannot be treated 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, which implement a predefined time schedule. No dynamic control is implemented in the sewer system.

3.3.2. Control strategy 1

This first control strategy focuses on the elimination of peak ammonia concentrations in the river downstream of the treatment plant. For this, an ammonia sensor is located in the river at the point where the highest concentrations of ammonia occur; this is at the overflow Station. The central idea of the controller is to avoid overloading of the treatment plant as long as the river is not in a critical condition with respect to ammonia. In other words, bypassing is allowed in low ammonia situations. Once river ammonia concentrations rise too high, the bypass is reduced by putting more water through the biological treatment.

The overloading of the treatment plant is controlled on the basis of the ammonia measurement in the river with a proportional controller with a limiter on the bypass flow. 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 set point concentration of 1.5 mg/l for (unionized plus ionized) ammonia was chosen based on the Fundamental Intermittent Standards (FIS) of UPM (FWR, 1998). These criteria take the concentration of unionized ammonia (NH_3) in the water into consideration. According to these criteria the concentration of NH_3 should not exceed 0.03–0.05 mg/l for more than 24 h with a return period of 1 month. With a pH of around 7.5, which is the value most frequently encountered in the Speibeek (Van Assel, 2000b), an NH_3 concentration of approximately 0.03 mg/l leads to the limit of 1.5 mg/l for total ammonia. The proportional constant was chosen in such a way that the maximum overloading of the plant ($4Q_{14}$) was reached if the river ammonia concentration attained 2.5 mg NH_4-N/l.

Some safety measures are included in the strategy as well. For instance, the overloading of the treatment plant is only activated when the storm tank is completely filled. In addition, a supervisory controller on the sludge blanket is implemented to prevent massive

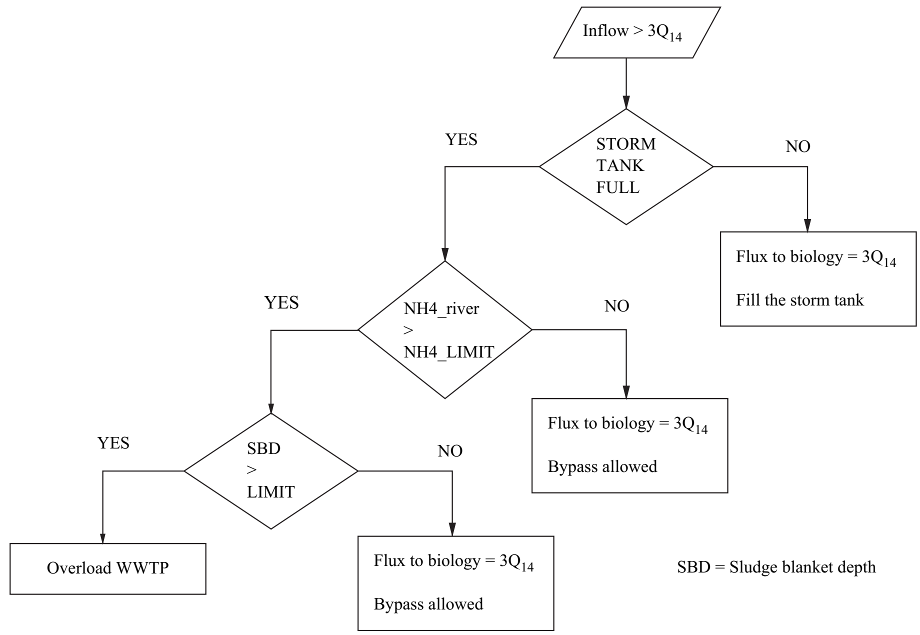

Fig. 5. Overview of the first control strategy.

sludge washout. If there is any risk of sludge loss via the settler (defined as the sludge blanket reaching a certain height, i.e. 0.5 m) the flow is restricted again to $3Q_{14}$. A schematic overview of the controller is given in Fig. 5.

3.3.3. Control strategy 2

Control strategy 2 extends control strategy 1 in order to also take advantage of improved operation of the sewer system. Simulations indicated that the hydraulic capacity of the connection between the storage tank at Deinsesteenweg and the overflow Station was only completely used when the storage tank was completely filled. This is due to the fact that this flow depends on the head of water in the tank. It was therefore evaluated whether adding a pump to this system would improve system performance since in this way the hydraulic capacity of the pipe could be completely used, even before the tank is 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. To protect the plant, the pump is only activated when the plant is not hydraulically overloaded.

A summary of the different control strategies is shown in Table 1, while the location of the sensors is shown in Fig. 4.

3.4. Model simplifications

3.4.1. Sewer model

Starting from the detailed Hydroworks model, a simplified Kosim model was constructed. The Kosim model of the complete catchment of Tielt consists of 33 subcatchments, 18 storage elements, 16 transport elements and one flow splitter and is shown in Fig. 6 (Van Assel and Carrette, 2001). It was found that total overflow volumes and overflow peak discharges were modelled with the same accuracy in both models. A comparison between Hydroworks- and Kosim-based predictions of the overflow volumes of two consecutive rain events is given in Fig. 7. Consequently, the simplified sewer model could be used for control tuning purposes.

3.4.2. Treatment plant model

Some phenomena were tried to be excluded from the model in order to simplify the model. First, the settler model described by Takács et al. (1991) was replaced by a conceptual model (point settler). In this model, a fixed fraction of the incoming solids is directed towards the

Table 1
Summary of the three control strategies tested

Name	Description
Reference control strategy	Local control of the storm tank, 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 WWTP is not overloaded

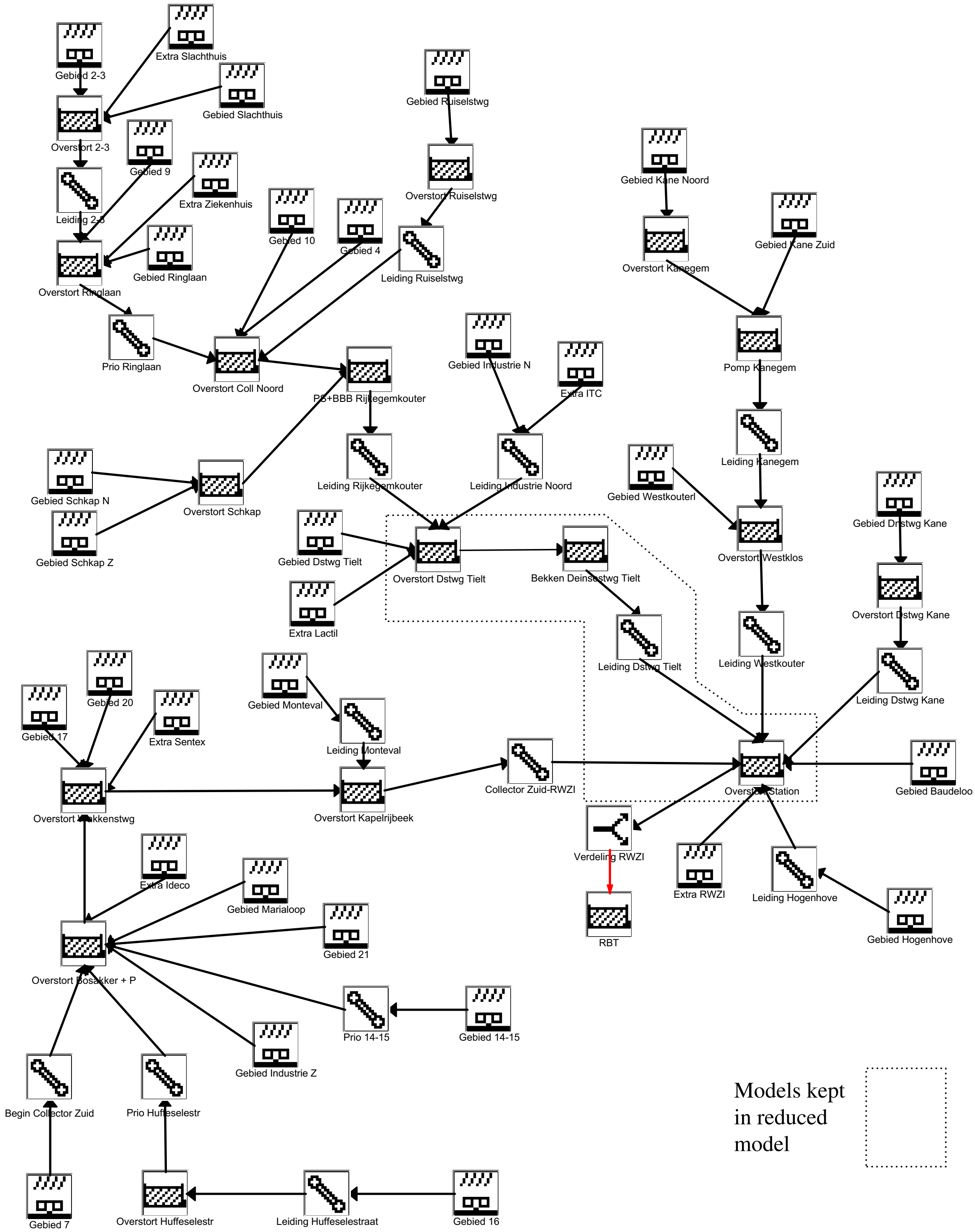

Fig. 6. Overview of the Kosim model of the Tielt sewer system.

effluent, while the remaining part is concentrated in the return/waste sludge. Second, the bioreactor oxygen dynamics were taken out, assuming the complete absence of oxygen in the non-aerated case and no limitation of the biomass by oxygen in the aerated case. In this way a fast process (thus requiring small integration time steps) was eliminated from the model, which would, in principle allow faster numerical integration. However, since the control strategy allows hydraulic overloading of the plant, both the oxygen dynamics and the behaviour of the sludge blanket in the settler are important phenomena during storm events.

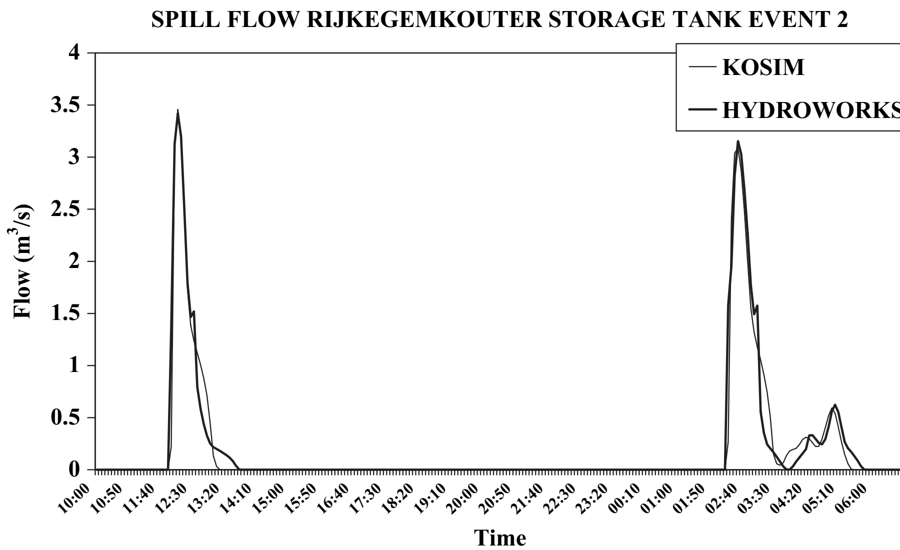

Fig. 7. A comparison of the overflow volumes predicted by Hydroworks and by Kosim.

As a result the proposed model reductions of the treatment plant model could not be used as they would not allow to realistically describe the behaviour of the treatment plant during storm conditions. More details can be found in Meirlaen and Vanrolleghem (1999).

3.4.3. River model

The river model is built as a series of completely stirred tank reactors (CSTRs) to approximate the hydraulic behaviour of the river. Since only the complex mechanistic model of the Poekebeek was available, a pragmatic approach had to be followed to build a simplified model of the Speibeek. The tanks were chosen such that all important inflows (like side streams or CSOs) could be taken into account. Parameters were taken according to earlier experience in calibrating this type of models for small rivers in Flanders (Meirlaen et al., 2001).

Two different models were used to describe the quality of the river. The first model was part of the control model and only considered transport and mixing of the relevant model components (e.g. ammonia). Simulations showed that the error made by omitting the conversions (e.g. ammonification, nitrification) were small (results not shown).

The second, more complex model was only used for the evaluation of the secondary objectives. It was a submodel of the RWQM1 (Reichert et al., 2001) to describe the biological conversions taking place in the river. The most important differences with the full RWQM1 are the lumping of the two-step nitrification into a one-step nitrification process with one type of nitrifying biomass. Moreover, no pH variations, algae or consumers were taken into account. Since very few data were available about the water quality of this small river and calibration was therefore very limited, this model should be considered a hypothetical model, which can, however, be used to evaluate the impact of the different control strategies.

3.5. Model reductions

3.5.1. Sewer mode

Since the most important overflows are located close to the treatment plant (both the overflow at Deinsesteenweg and at Station), only four of the 68 elements of the full Kosim model were retained in the control model. These were the CSO structure at Deinsesteenweg, the storage tank at Deinsesteenweg, the pipe connecting this CSO with Station and the overflow structure at Station itself. This resulted in a substantial model simplification and only this part of the sewer model was implemented into WEST®. 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. The part retained in the control model is shown in Fig. 6.

3.5.2. Treatment plant model

Since the complete treatment plant is important for the river water quality, no upstream or downstream parts could be left out in this case study. However, if the sludge treatment processes would also have been taken into account in the full treatment plant model (e.g. to model sludge treatment costs), this part could clearly be left out for the control model.

3.5.3. River model

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 Station where the ammonia measurement is located, resulted in a control model of only six tanks.

3.5.4. Time boundary

The first important rain event only occurs during the seventh day of the studied period. Since the controllers do not act before the end of the sixth day, the behaviour of the system up to that moment is independent of the controller. Therefore, a relocation of the time boundaries can be performed, i.e. one simulation was performed to determine the state of the 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 single simulation.

3.5.5. Secondary objectives

In the example used in this study an attempt has been made to maximize the model reduction via system boundary relocation and submodel selection, leading to a so-called control model. The control system only focused on the ammonia concentration and this allowed eliminating, for instance, the section of the river downstream of the ammonia sensor. The secondary objectives looked at in this study are the minimum oxygen concentration in the whole downstream river stretch (evaluated at each time instant by taking the smallest oxygen concentration of all downstream tanks), the maximum time the oxygen is below a given limit (4 mg O_2/l) and the time the river concentration at the critical section is above a given ammonia limit. For these secondary objectives, the complete river model with conversions is used. Finally, the robustness of the different control strategies is calculated, as another means of evaluating the performance of the strategy.

3.6. The resulting control model

The WEST® simulator was originally used mainly for simulation of wastewater treatment plants and an extensive WWTP modelbase is available (Vanhooren et al., 2003). Both the simplified runoff/sewer model and the tanks-in-series river model are now implemented in this package as well. Hence, the three parts of the integrated urban wastewater system (IUWS) are now available in a single software tool and, thanks to this, linking of the submodels is straightforward. Moreover, problems with file or data transfer between different simulators are avoided and, most importantly, simultaneous simulation is possible (Meirlaen et al., 2001). A schematic overview of the resulting control model in WEST® is given in Fig. 8.

For the evaluation of the secondary objectives, a separate river model was used, which included the river conversion processes and the complete downstream river part. In this way, the overall oxygen dynamics of the river could be judged. Since here the main interest is in the river subsystem, all inputs to the river are specified as input files calculated at particular locations with the control model. However, particular attention has to be paid when creating these influent files. As CSOs are very dynamic, the time interval used in the input files must be rather small, e.g. 1 min. In order to avoid huge files, this time interval might then be relaxed to, for instance, 15 min in other situations (e.g. dry weather).

4. Simulation results

4.1. Performance of the controllers

A two week period was selected from the available data (6 months) to test the control strategies. In these two weeks, two major storms (on days 6 and 7) with each two rain peaks are present.

The different control strategies are evaluated at different levels. First, the treatment plant effluent concentrations are compared. In the second paragraph, the resulting ammonia concentrations in the river are shown and discussed. Next, the effect of the control strategies on the resulting in-stream oxygen concentrations is evaluated. Finally, the robustness of the controllers towards system changes will be calculated and discussed.

The effluent concentrations of the treatment plant for the reference control and strategy 2 are shown in Fig. 9. The strategy 1 effluent is very close to the strategy 2 effluent and not shown in the graph. It can be seen that the effluent concentrations are not depending a lot on the control strategy applied, even though the plant is overloaded during certain periods. In the reference control case, the inflow goes up to $3Q_{14}$ (design capacity), while in control strategy 2 the maximum overload factor is $4Q_{14}$. Apparently, since the treatment plant is an extended aeration system, sufficient nitrification capacity is available. Also, no major increase of the effluent suspended solids concentration was noted in the simulation results. This is probably a good assumption since the sludge of extended aeration systems is known to settle well (Arhan et al., 1996).

In Fig. 10, however, the effect of the control strategy can clearly be seen, since the river ammonium concentration with the controllers active, is always lower than or equal to the concentration in the reference case. However, the effect is not always caused by the same mechanism. In the first part of each storm (from day 6.5 to 6.7 and from 7.1 to 7.3), the storage tank at Deinsesteenweg is not completely filled and, hence, the flow rate of water to the treatment plant is not maximized in the reference case and in strategy 1. By adding a pump in the sewer system at the storage tank

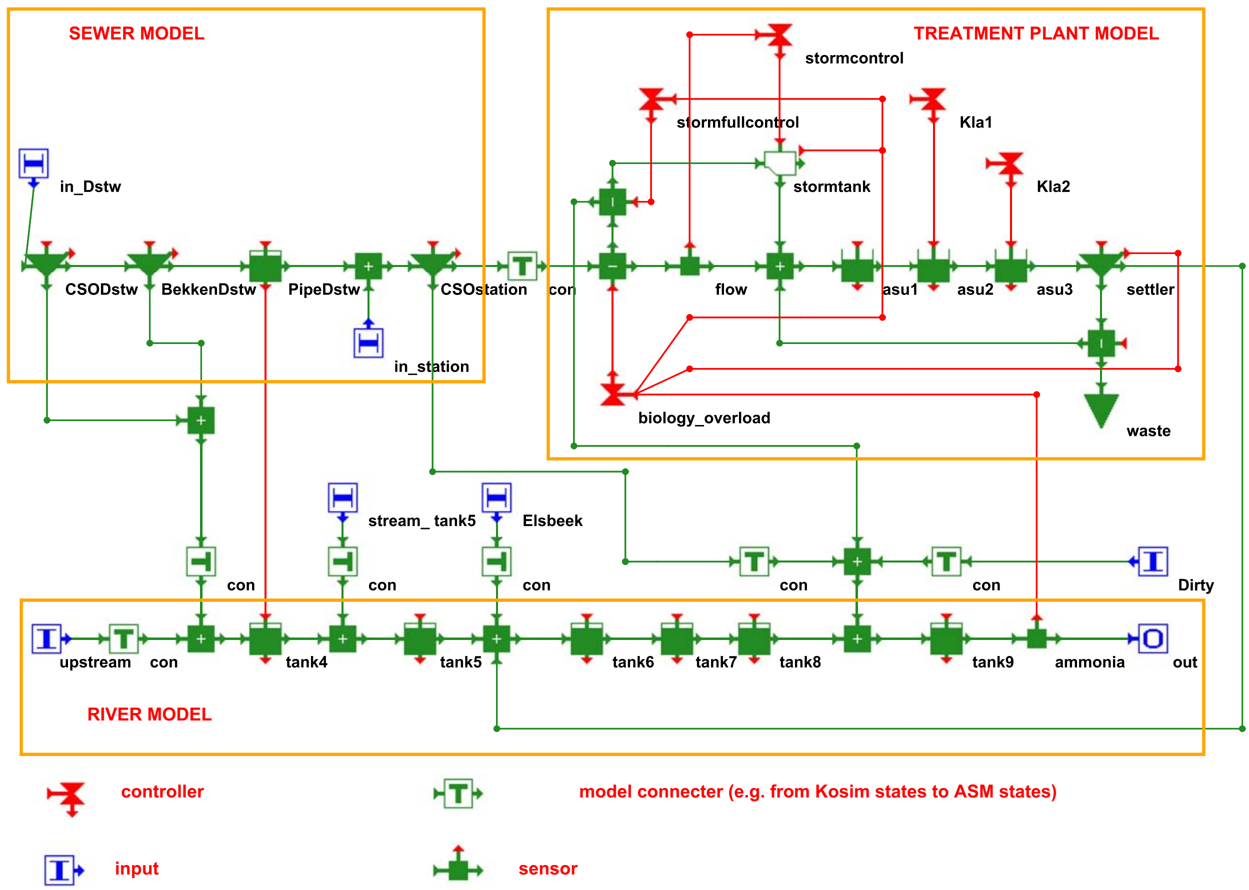

Fig. 8. The control model as implemented in WEST®.

(strategy 2, Fig. 10, right), more water can be sent downstream, even without the tank being completely filled. The additional water which is sent downstream, saves some space in this storage tank, which can be used later on to store polluted water. Due to the limited capacity of the pipe downstream of the storage tank at Deinsesteenweg, not all of the combined sewer overflow can be avoided, leading to peak ammonia concentrations in the river in the early stages of the events. If the hydraulic capacity could be increased, a more substantial reduction in river ammonia concentration can be expected.

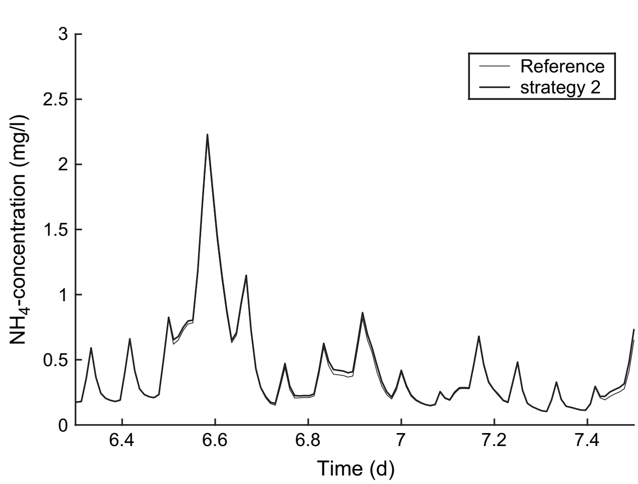

Fig. 9. The resulting effluent ammonia concentration in both the reference control case and control strategy 2.

In the second part of the evaluated storms (days 6.7–6.8 and 7.3–7.5), the storm tank is filled in all cases, so the addition of the pump does no longer have a beneficial effect. However, in these conditions the overloading of the treatment plant by the first and the second control strategies is active. 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 study. It can be seen that in the second part of the selected rain events, the ammonia concentration can be controlled to this set point. The effect of the control strategies on the ammonia concentrations in the river can clearly be noticed from the difference in the simulation results between control strategies 1 and 2. In the first case, an improvement in river water quality is only noticed in the second part of the storm (Fig. 10, left), while in the second case, both parts of the storm period benefit form the control actions (Fig. 10, right). However, it can be

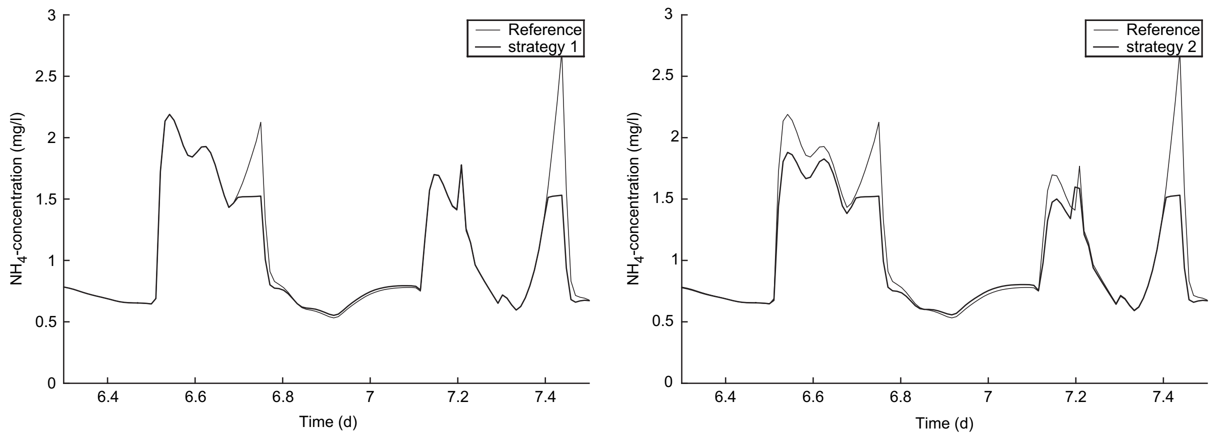

Fig. 10. The resulting effluent ammonia concentration in both the reference control cases compared to strategy 1 (left) and 2 (right).

concluded that sufficient control authority is not there to completely control the first peak.

Fig. 11 shows the evolution of the overall minimum oxygen concentration in the whole downstream river stretch in the reference case compared to strategy 1. It can be seen that the minimum oxygen evolution is more or less the same in the two cases. Because the secondary objectives of the control strategy are not significantly worse, the control strategy may be implemented.

4.2. Evaluation of the robustness of the control system

As discussed before, a controller is always tuned for a given situation and system. As a model never represents reality perfectly, it is important to know how sensitive the controller is towards differences in the system to which it is applied. The robustness index as introduced before, is one way to express this and will be discussed for the used control strategies.

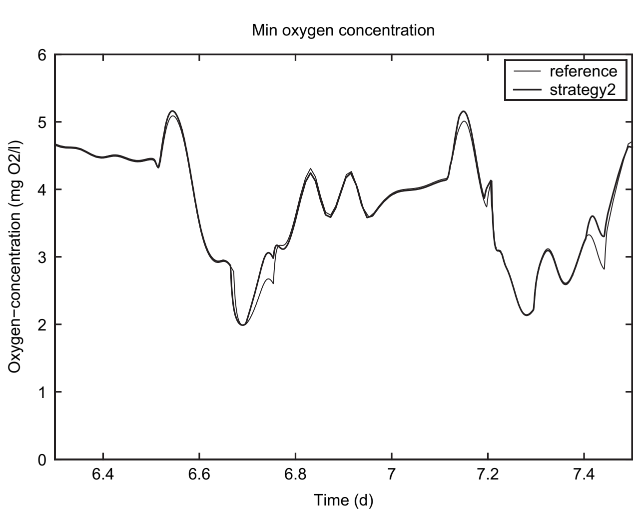

Fig. 11. The overall minimum oxygen concentration in the reference control case compared to strategy 2.

The control strategies were tested for robustness against three changes to the system. In the first case, the growth rate of the nitrifying biomass in the treatment plant was temporarily reduced by 10% compared to the reference case. This case mimics for instance a slightly toxic influent entering the treatment plant. In the second case, the aeration capacity was reduced by 10% to mimic mechanical problems with a blower. In the third case, the nitrogen content of the sewage was increased by 10%. All expected ranges ($\Delta\theta$) were chosen to be 20% of their nominal value.

The effect of reducing the aeration constant Kla by 10% on the performance of the reference control strategy is shown in Fig. 12. For both the ammonia maximum and the oxygen minimum, the system change causes the quality of the river to worsen. However, for some system changes the criterion value improved. Decreasing μ_A (maximum growth rate for autotrophic bacteria), for example, led to an increased minimum oxygen concentration, which is quite unexpected. The reason is that the lower μ_A leads to a lower oxygen consumption in the treatment plant and to a higher oxygen concentration in the effluent, and hence also to higher oxygen levels in the river. The sensitivities and the robustness were tested for two criteria: the maximum ammonia concentration, and the time that the ammonia concentration was above 1.5 mg NH_4-N/l.

From Table 2 it can be seen that for the two criteria, the robustness of the different control strategies is similar, except for the maximum ammonia concentration where the reference control strategy is more robust. This is somewhat logical, since the controllers have been tuned to perform good in a given situation on the maximum ammonia concentration, and are hence more sensitive towards changes for this criterion. For the other criteria, no substantial change in robustness is noted, but the general performance is better. It can therefore be concluded that it is relatively safe to use the suggested control strategies. The robustness index shows

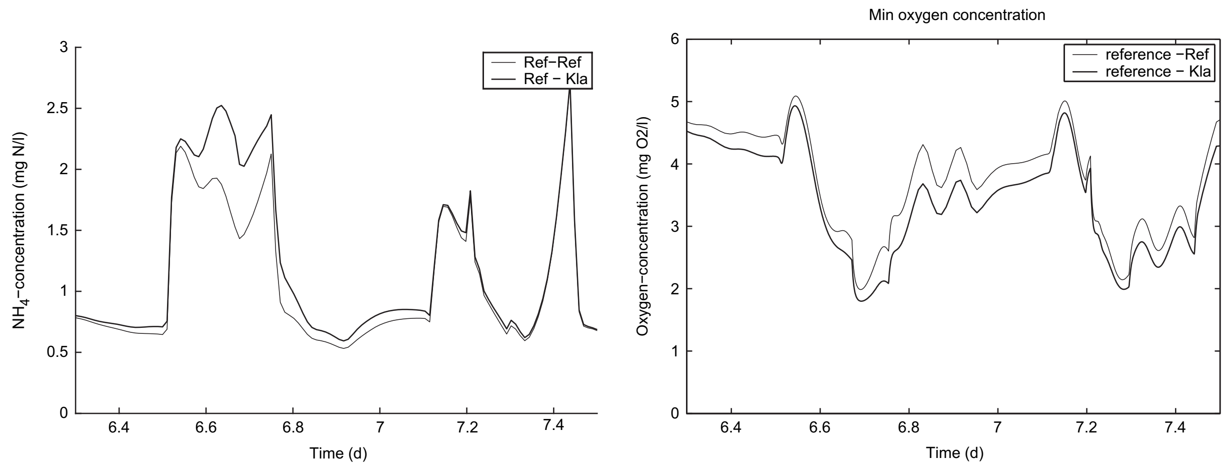

Fig. 12. The effect of the Kla decrease by 10% on the resulting ammonia concentration (left) and oxygen concentration (right) for the reference control strategy.

that the controller will probably work well on the real system, even if it is designed and tuned on an approximate model.

5. Conclusions

Two approaches to gain calculation time of an integrated (sewer, WWTP and river) simultaneously simulating model were outlined and illustrated in this paper. First, the use of mechanistic surrogate models is suggested to be a promising approach to replace the complex equations with simplified ones, e.g. replace the partial differential equations of 'de Saint-Venant' with a tanks-in-series model. These models can be calibrated on the basis of data generated by the complex models. Second, model reduction through boundary relocation has been introduced. By relocating the upstream and downstream system boundaries, parts of the model can be left out when tuning the control strategies. All this results in a simplified model, which can be used for the development of immission-based control strategies.

Table 2
Robustness of the different control strategies for different criteria to changes in μ_A, Kla and TKN (for more details, see text)

Strategy	Disturbance	Max, NH_4	Duration NH_4
Ref	μ_A	−0.0087	0.5231
	Kla	−0.1777	−1.5200
	TKN	−0.4038	−1.02
Robustness		3.9253	0.9098
Strategy 1	μ_A	−0.1523	−0.2921
	Kla	−0.7781	−2.3428
	TKN	−0.3713	−1.1194
Robustness		1.9799	0.6651
Strategy 2	μ_A	−0.2023	−0.4444
	Kla	−0.9551	−3.2585
	TKN	−0.4401	−1.5835
Robustness		1.6162	0.5328

It was shown for the Tielt case study that the simulated immission-based control strategy was able to improve the ammonia concentration in the river, while there was no deterioration with respect to oxygen. It can hence be concluded that immission-based real-time control can be a valid option in integrated urban water management, with regard to WFD compliance. However, considerations on the effects of these strategies on the ecological status are beyond the scope of this study as the relation between chemical water quality and ecology is subject of important research efforts.

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References

Arhan, Y., Oturk, I., Ciftci, T., 1996. Settling and dewatering characteristics of sludge from baker's yeast production wastewater treatment. Water Sci. Technol. 34 (3–4), 459–467.

Bauwens, W., Vanrolleghem, P., Smeets, M., 1996. An evaluation of the efficiency of the combined sewer waste water treatment system under transient conditions. Water Sci. Technol. 33 (2), 199–208.

Beck, M., 2005. Vulnerability of water quality in intensively developing urban watersheds. Environ. Model. Softw., this issue, doi: 10.1016/j.envsoft.2004.02.002.

Beck, M., Young, P., 1975. A dynamic model for DO–BOD relationships in a non-tidal stream. Water Res. 9, 769–776.

Blöch, H., 2001. EU policy on nutrients emissions: legislation and implementation. Water Sci. Technol. 44 (1), 1–6.

Butler, D., Schütze, M., 2005. Integrating simulation models with a view to optimal control of urban wastewater systems. Environ. Model. Softw., this issue, doi: 10.1016/j.envsoft.2004.02.003.

Carrette, R., Bixio, D., Thoeye, C., Ockier, P., 2001. Full-scale application of the IAWQ ASM No.2d model. Water Sci. Technol. 44 (2–3), 17–24.

Council of the European Communities, 2000. Directive 2000/60/EC of the European parliament and of the council of 23 October 2000 establishing a framework for Community action in the field of water policy. Official Journal L327, 1.

Cowie, G., Borrett, S., 2005. Institutional perspectives on participation and information in water management. Environ. Model. Softw., this issue, doi: 10.1016/j.envsoft.2004.02.006.

Entem, S., Lahoud, A., Yde, L., Bendsen, B., 1998. Real time control of the sewer system of Boulogne Billancourt—a contribution to improving the water quality of the Seine. Water Sci. Technol. 37 (1), 327–332.

Erbe, V., Risholt, L., Schilling, W., Londong, J., 2002. Integrated modeling for analysis and optimization of wastewater systems—the Odenthal case. Urban Water 4 (1), 141–150.

Fath, B., Beck, M., 2005. Elucidating public perceptions of environmental behavior: a case study of Lake Lanier. Environ. Model. Softw., this issue, doi: 10.1016/j.envsoft.2004.02.007.

Fronteau, C., Bauwens, W., 1999. Modellering van overstortemissies en bepaling van de impact ervan. @wel-Water 4, 1 (in Dutch).

FWR, 1998. Urban Pollution Management (UPM). A Planning Guide for the Management of Urban Wastewater Discharges During Wet Weather, second ed. Foundation for Water Research, Marlow, UK.

Goethals, P., De Pauw, N., 2001. Development of a concept for integrated ecological river assessment in Flanders, Belgium. J. Limnol. 60 (Suppl. I), 7–16.

Havens, K., Schelske, C., 2001. The importance of considering biological processes when setting total maximum daily loads (TMDL) for phosphorus in shallow lakes and reservoirs. Environ. Pollut. 113 (1), 1–9.

Heip, L., Van Assel, J., Swartenbroeckx, P., 1997. Sewer flow quality modelling. Water Sci. Technol. 36 (5), 177–184.

Henze, M., Gujer, W., Mino, T., van Loosdrecht, M., 2000. Activated Sludge Models ASM1, ASM2, ASM2d and ASM3. Scientific and Technical Report No. 9. IWA Publishing, London, UK.

Kallis, G., Butler, D., 2001. The EU water framework directive: measures and implications. Water Policy 3 (2), 125–142.

Meirlaen, J., Huyghebaert, B., Sforzi, F., Benedetti, L., Vanrolleghem, P., 2001. Fast, simultaneous simulation of the integrated urban wastewater system using mechanistic surrogate models. Water Sci. Technol. 43 (7), 301–308.

Meirlaen, J., Van Assel, J., Vanrolleghem, P., 2002. Real time control of the integrated urban wastewater system using simultaneously simulating surrogate models. Water Sci. Technol. 45 (3), 109–116.

Meirlaen, J., Vanrolleghem, P., 1999. Development of a Reduced Model of the IAWQ Activated Sludge Model No. 2d. BIOMATH Technical Report, Ghent University, Gent, Belgium.

Nielsen, M.K., Carstensen, J., Harremoës, P., 1996. Combined control of sewer and treatment plant during rainstorm. Water Sci. Technol. 34 (3–4), 181–187.

Paulsen, O., 1986. Kontinuierliche Simulation von Abflüssen und Schmutzfrachten in der Trennentwässerung. Mitteilunges des Institutes für Wasserwirtschaft. Universität Hannover 62 (in German).

Petruck, A., Cassar, A., Dettmar, J., 1998. Advanced real time control of a combined sewer system. Water Sci. Technol. 37 (1), 319–326.

Pleau, M., Colas, H., Lavallée, P., Pelletier, G., Bonin, R., 2005. Global optimal real-time control of the Québec urban drainage system. Environ. Model. Softw., this issue, doi: 10.1016/j.envsoft.2004.02.009.

Pleau, M., Pelletier, G., Colas, H., Lavallée, P., Bonin, R., 2001. Global predictive real-time control of Quebec Urban Community's westerly sewer network. Water Sci. Technol. 43 (7), 123–130.

Rauch, W., Aalderink, H., Krebs, P., Schilling, W., Vanrolleghem, P., 1998. Requirements for integrated wastewater models—driven by receiving water objectives. Water Sci. Technol. 38 (11), 97–104.

Rauch, W., Harremoës, P., 1999. Genetic algorithms in real time control applied to minimize transient pollution from urban wastewater systems. Water Res. 33 (5), 1265–1277.

Reda, A., 1996. Simulation and control of stormwater impacts on river water quality. PhD, Imperial College, London, UK.

Reichert, P., Borchardt, D., Henze, M., Rauch, W., Shanahan, P., Somlyody, L., Vanrolleghem, P., 2001. River Water Quality Model No. 1 (RWQM1). Scientific and Technical Report No. 12. IWA Publishing, ISBN: 1-900222-82-5.

Rousseau, A.N., Mailhot, A., Quilbé, R., Villeneuve, J.-P., 2005. Information technologies in a wider perspective: integrating management functions across the urban–rural interface. Environ. Model. Softw., this issue, doi: 10.1016/j.envsoft.2004.02.008.

Rousseau, D., Verdonck, F., Moerman, O., Carrette, R., Thoeye, C., Meirlaen, J., Vanrolleghem, P., 2001. Development of a risk assessment based technique for design/retrofitting of WWTPs. Water Sci. Technol. 43 (7), 287–294.

Schilling, W., 1989. Real-Time Control of Urban Drainage Systems. The State-of-the-Art. Scientific and Technical Reports No. 2. IAWQ, London, UK.

Schleiter, I., Borchardt, D., Wagner, A., Dapper, T., Schmidt, K., Schmidt, H., Werner, H., 1999. Modelling water quality, bioindication and population dynamics in lotic ecosystems using neural networks. Ecol. Model. 12, 271–286.

Schütze, M., Butler, D., Beck, B., 1999. Optimisation of control strategies for the urban wastewater system—an integrated approach. Water Sci. Technol. 39 (9), 209–216.

Schütze, M., Butler, D., Beck, M., 2002a. Modelling, Simulation and Control of Urban Wastewater Systems. Springer Verlag, London, UK.

Schütze, M., To, T., Jumar, U., Butler, D., 2002b. Multi-objective control of urban wastewater systems. In: International Federation of Automatic Control 15th IFAC World Congress, Barcelona, 21–26 July 2002.

Schütze, M., Butler, D., Beck, M., 2001. Parameter optimisation of real-time control strategies for urban wastewater systems. Water Sci. Technol. 43 (7), 139–146.

Takács, I., Patry, G.G., Nolasco, D., 1991. A dynamic model of the clarification-thickening process. Water Res. 25, 1263–1271.

Vaes, G., Berlamont, J., 1999. Emission predictions with a multi-linear reservoir model. Water Sci. Technol. 39 (2), 9–16.

Van Assel, J., 2000a. Innovation Project INI103401—Pilot Study Tielt and Poekebeek: Final Technical Reports. Aquafin N.V., Aartselaar, Belgium.

Van Assel, J., 2000b. Integrated modelling of the Tielt and Poekebeek catchment. In: Proceedings Integrated Modelling User Group Conference. Prague, Czech Republic, April 12–14, 2000.

Van Assel, J., Carrette, R., 2001. A practical application of integrated pollution modelling in Flanders (Belgium): the catchment of Tielt. Water Sci. Technol. 45 (3), 125–130.

Vanhooren, H., Meirlaen, J., Amerlink, Y., Claeys, F., Vangheluwe, H., Vanrolleghem, P., 2003. WEST: modelling biological wastewater treatment. J Hydroinform. 5 (1), 27–50.

Vanrolleghem, P., Gillot, S., 2002. Robustness and economic measures as control benchmark performance criteria. Water Sci. Technol. 45 (3), 117–126.

Vanrolleghem, P., Schilling, W., Rauch, W., Krebs, K., Aalderink, H., 1999. Setting up measuring campaigns for integrated wastewater modelling. Water Sci. Technol. 39 (4), 257–268.

Weinreich, G., Schilling, W., Birkely, A., Moland, T., 1997. Pollution based real time control strategies for combined sewer systems. Water Sci. Technol. 36 (8–9), 331–336.

Wils, C., 2000. Metingen van korte en lange termijn impact van overstorten op de ontvangende waterlopen. @wel-Water 2000 (4), 1–6 (in Dutch).