Real time control of the integrated urban wastewater system using simultaneously simulating surrogate models

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Abstract The urban wastewater system (sewer and treatment plant) has a major impact on the river water quality of urban streams. To minimise this impact, real time control is a valuable option. Since the ultimate goal of any control strategy is to optimise the quality of the river system, it is useful to take pollutant immissions into account when determining the control strategy and/or the setpoints of the controller. However, a simultaneously simulating model of the complete system is needed in order to allow design and evaluation of such control strategies.

In this work an integrated model of the urban wastewater system is created. This has been accomplished by implementing surrogate models of the three subsystems within a single software platform. The coupled submodels are subsequently used in a semi-hypothetical case study to optimise the resulting river water quality. An ammonia sensor in the river has been used to control the amount of water treated biologically in the treatment plant. It was shown that this integrated control could lower the peak ammonia concentration in the part of the river downstream of the treatment plant. Hence, a proof of principle has been given that the use of measurements in the river to perform control actions in the sewer system and the treatment plant is a promising option.

Keywords Integrated urban wastewater system; modelling; real time control; RWQM1

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Introduction

The urban wastewater system consists of three major parts: the sewer system, the wastewater treatment plant and the receiving water (river, lake). Both the sewer system and the treatment plant have a detrimental impact on the quality of the receiving water, the former discontinuously via combined sewer overflows, the latter continuously via the effluent which is not completely pollutant free. Real time control might be used to minimise the impact of the urban water on the river. This might be done by optimising the performance of the sewer system and/or treatment plant separately. These control strategies usually aim at minimising the amount of water spilled via CSO (e.g. Pleau *et al.*, 2001), or to optimise the performance of the treatment plant under storm conditions (e.g. Lessard and Beck, 1990; Harremoës *et al.*, 1993; Entem *et al.*, 1998). It is obvious that these control strategies improve the performance of the system compared to the non-controlled case. However, when only looking at one part of the system, e.g. the sewer system, and not taking into account the worse effluent quality from the treatment plant by overloading, one might not fully take into account the overall goal of the control strategy (Bauwens *et al.*, 1996). It has, for example been shown by Rauch and Harremoës (1999) that minimising the total volume or pollution load, hence only looking at the emissions, does not guarantee the best resulting water quality. Next to the pollution load entering the river, also the timing and/or the location of the pollution entering the river may be important. Consequently, to be able to take most of the possible interactions into account an integrated model of the system is necessary.

Different authors have already tried to develop such an integrated model. Schütze *et al.*

(1998) describe the SYNOPSIS simulator, which uses different existing models in different software packages. The communication between the software packages is taken care of by various interface routines, but is fairly complex. On the other hand, in the present implementation of SYNOPSIS, only the sewer system and the treatment plant run in parallel, while the river model is run afterwards with input files from the other parts. Taylor *et al.* (2000) recently described an integrated catchment simulator, which is able to model the three subsystems in parallel, by automation of the communication between the Mouse, Stoat and Mike programs. The work described in this paper attempts to integrate the three models in one package, WEST® (Hemmis NV, Kortrijk, Belgium), thus avoiding problems of file or data transfer and simulating the entire system simultaneously.

Integrated modelling

Three problems are encountered when developing an integrated model that is to be used for developing an integrated control system or for system optimisation. First, the state-of-the-art models use different variables to describe the aquatic system (e.g. BOD, COD, TOC, . . . to describe organic pollution). Second, 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. Third, 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.

We have tried to solve these problems. The first problem is handled by carefully selecting models and developing consistent translators between the variables of one submodel and the variables of another. The Activated Sludge Models (ASM, Henze *et al.*, 1987, 1995; Gujer *et al.*, 1999) are taken here as a starting point, since these models are already known for a long time, and are considered to be the state-of-the-art models to describe activated sludge processes. These models use COD as a measure for organic pollution and describe the dynamics of both organics and nutrients. The frequently used river models, like Qual2e, Isis or Mike11, typically use BOD as a measure for organic pollution. Since there is no fixed relationship between COD and BOD, it is difficult to link these two models. Since this problem was commonly encountered, the Task Group for river water quality modelling of the IWA, developed and recently proposed the RWQM1 (Shanahan *et al.*, 2001; Reichert *et al.*, 2001; Vanrolleghem *et al.*, 2001). This model is, like the ASM-models, COD-based, and also has different types of biomass as state variables, which makes it more suited for coupling with the ASM-models. However, the state variables of e.g. ASM1 and RWQM1 are not exactly the same, such that conversion from the ASM state variables to the RWQM1 state variables still is necessary. By carefully considering the fate of certain ASM components in riverine conditions, a connector between the ASM1 and the RWQM1 has been developed (Meirlaen *et al.*, in preparation b). This connector has closed mass balances, and it is possible to include the effect on the biomass of the different environmental conditions (like substrate concentration or temperature) in the treatment plant and in the river. A part of the biomass might for example become inactive. The connection between the sewer system and the ASM-models was already discussed by Fronteau *et al.* (1997).

The problem of the complex hydraulic equations is handled by simplifying the models describing the hydraulic behaviour of the system. For the sewer system, a catchment runoff model similar to the Kosim model (Paulsen, 1986) is used, while for the river model a series of completely stirred tank reactors (CSTRs) model is chosen. When calibrated on a sufficient amount of adequate data, these mechanistic surrogate models are known to be sufficiently accurate in describing the system (see Beck and Young (1975) and Reda (1996) for the river system, Fronteau (1999), for the Kosim part). These data can be collected during measuring campaigns or, alternatively, be generated once from a complex hydraulic model (which uses the "de Saint-Venant" equations). The approach taken to develop such a simplified hydraulic model on the basis of reality, via a complex hydraulic model is shown in Figure 1. Since data collection is an expensive and time consuming task, it is probably not possible to collect a sufficient amount of data to calibrate the mechanistic surrogate models directly from real data Vanrolleghem *et al.*, 1999). Therefore, the data collection should be carried out, not as a function of the calibration of the surrogate model, but as a function of the calibration of the complex hydraulic models. Once these well-known models are calibrated and validated on the basis of real data, extra simulations can be performed with these models in order to generate extra virtual data. These virtual data, together with the already collected field data, can then be used to calibrate the surrogate models like Kosim, or the CSTRs in series river model (Meirlaen *et al.*, 2001).

The third problem has been solved by implementing the models of the three subsystems into a single software package, WEST®. This package was first developed for simulation of wastewater treatment plants and has been extended with models both for the sewer and the river systems. The equations of the Kosim package are written in discrete time steps and were, in order to be solved by the numerical algorithms in WEST®, to be transformed into differential equations. On the other hand, implementing the RWQM1 and some of its submodels was not a problem since these models have a very similar structure compared to the ASM-models, which were already present in the model base. Other models that had to be implemented were the connectors between the different models of the subsystems.

In this way it is possible to create an integrated simultaneously simulating model, which is sufficiently fast to allow optimisation of a control strategy on a realistic case. A case study on the catchment of Tielt will be outlined in the next section. A proof of principle that integrated control is a promising option will be illustrated on this catchment.

The Tielt catchment and model description

Description of the catchment

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 water courses 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

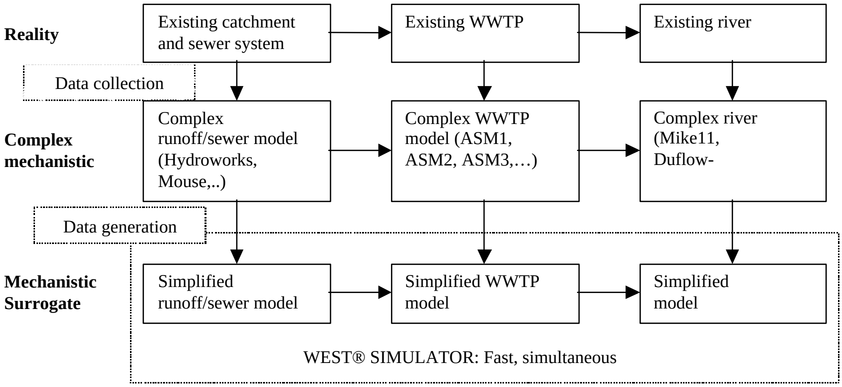

Figure 1 From reality to surrogate models using complex hydraulic model

and some surrounding villages. 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. 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. Four important overflows are present on the Speibeek. A general outline of the parts of the system considered are shown in Figure 2. 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 most upstream CSO acts as the main source of flow during rain events.

The rainfall

During the TTP project, six months of rainfall data have been collected by several rain gauges in the catchment. However, to study the effect of the control strategy only two weeks out of these six months have been used. In these two weeks two important storms take place, each of the storms consisting of two major rainfall events.

The sewer system and the sewer models

The sewer system drains the area of the town of Tielt, together with some small surrounding villages. The total drained area is around 600 ha, about 250 of which are impervious. During heavy rain events several combined sewer overflows spill diluted wastewater directly in both the Poekebeek and the Speibeek. Since these streams have a very low base flow near their source, the overflows are the main source of water and, of course, pollutant input during overflow events. The sewer system has been modelled using both Hydroworks and Kosim software (Van Assel and Dierickx, 2000). The Kosim model consisted of 33 subcatchment, 18 storage elements, 16 transport elements and 1 flow splitter.

The treatment plant and treatment plant model

The treatment plant (design capacity 30,000 I.E.) has a Bio-Denipho process layout treatment plant (Carette *et al.*, 2001). It consists of three tanks, one is anaerobic, while the other two are intermittently aerated, in order to create the proper conditions for biological phosphorus removal together with the nitrification-denitrification processes. Some industrial discharges provide extra readily biodegradable COD and enhance in this way the biological phosphorus uptake. It was noticed that during the summer holiday of the industries the phosphate uptake decreased and hence, the effluent phosphate concentrations increased. The treatment plant has been modelled with the ASM2d process model (Henze *et al.*, 1999), while the settler model used is the one described by Takacs *et al.* (1991).

The Speibeek and the stream model

The river under study in this work is the Speibeek river. Near Tielt it is actually a very small stream, originating from the confluence of some ditches draining a rural area. The actual river stretch under study has a total length of about 7.5 km before entering the Oude Mandelbeek. The effluent of the treatment plant enters the river after about 2.5 km, while three of the combined sewer overflows are located upstream of the treatment plant, and the fourth one is situated 1.5 km downstream. At the last overflow (Station), a heavily polluted side stream enters the river. More upstream, some less polluted side streams enter the Speibeek (Figure 2).

The Speibeek has been modelled with a tanks in series model for the hydraulic part and dispersion processes, while a submodel of the RWQM1 model has been used to describe the conversion processes in the river. Not much data on the morphology and geometry of the river were available and hence the hydraulic part of the river was set up using experience from earlier calibration studies (Meirlaen *et al.*, in preparation a). Since these are rather rough assumptions, the river model most likely is to be considered a semi-hypothetical model. It was noticed that the effect of the overflows and the treatment plant effluent did not end before the confluence of the Speibeek with the Oude Mandel. To be able to make an overall judgement on the effect of these discharges and the effect of certain control options, the model was artificially prolonged with some extra tanks in series to a total length of 40 km.

A submodel of the full RWQM1 (Vanrolleghem *et al.*, 2001) was selected in order to obtain a model that describes the most important processes found in the Speibeek. An overview of the selected submodel is given in Table 1. Nitrification has been described by 1-step nitrification, as in the ASM-models since no information on nitrite concentrations was available. The corresponding RWQM1 equations have been grouped in such a way that the mass balances are still closed for the nitrification reactions. As oxygen concentration can become low in the river, denitrification might be an important process and has, hence, to be taken into account. Not much data were available on the water quality of the Speibeek, and this river model should be regarded as a hypothetical river model used to evaluate the effect of the control strategy. No sedimentation or resuspension processes have been taken into account, while sediment related processes also are neglected. This is a rather rough assumption since during high flows, some of the sediments are known to resuspend and will probably have an effect on the water quality during high flow periods.

The control strategy

The tested control strategy is exploiting the delay between the overflows upstream of the treatment plant and the overflow downstream of the treatment plant. The quality of

Table 1 The state variables and processes used in the submodel of the RWQM1 for the Speibeek

State variable		Processes
S_I	Inert soluble COD	Aerobic growth of heterotrophs with NH4
S_S	Readily biodegradable COD	Aerobic growth of heterotrophs with NO3
S_O	Oxygen	Anoxic growth of heterotrophs
S_NH4	Ammonia	Aerobic Respiration of heterotrophs
S_NO3	Nitrate	Anoxic respiration of heterotrophs
S_HPO4	Phosphate	Growth of nitrifiers
X_H	Heterotrophic biomass	Respiration of nitrifiers
X_N	Nitrifying biomass	Hydrolysis of X_S
X_I	Particulate inert COD	
X_S	Slowly biodegradable COD	

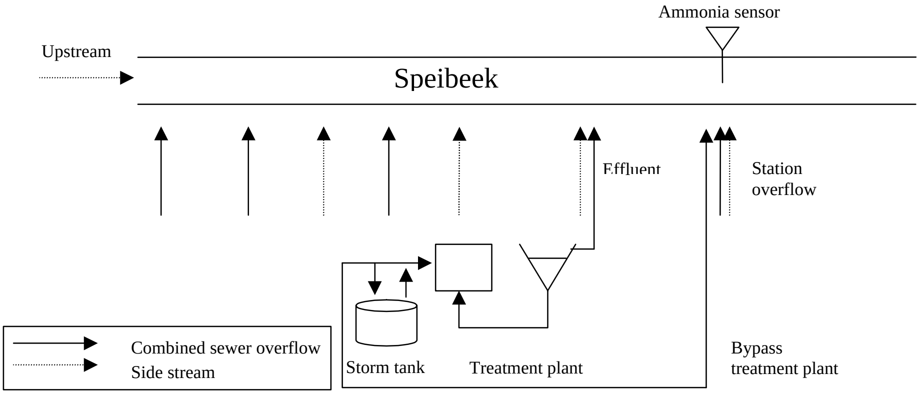

Figure 2 Overview of the discharges located along the Speibeek

the water downstream of the treatment plant might still be sufficiently good and the self-purification of the river sufficient to allow for some additional pollution load. An ammonia sensor located near the last overflow is used as input to a controller that determines the amount of water to be treated by the treatment plant. It should be noticed that water that is not accepted at the treatment plant will bypass and enter the river at the last overflow (Station). The base case, without this extra controller is as follows. When the flow to the treatment plant increases, up to 3 times dry weather flow (DWF) is directed to the biological treatment. When more water is entering the treatment plant (due to a higher water level in the sewer system), up to 3 times DWF is diverted to the storm tank, located on the treatment plant site. When the storm tank is filled with the most polluted water, the flow exceeding 3 times DWF is bypassed and spilled at the Station overflow.

The control strategy overloads the biological treatment plant as late as possible on the basis of the ammonia sensor. This means that as long as the measured ammonia concentration is below a given setpoint (here 1.5 mg NH_4-N/l), bypassing of the treatment plant is allowed as in the base case. However, when the measured ammonia concentration is above the setpoint, which means that the river can not take more untreated water, the biological treatment is overloaded with a flow up to 4 times DWF. A supervisory controller on the sludge blanket height restricts the inflow when the increased hydraulic loading of the plant leads to a risk of sludge loss via the effluent. In this way a measurement from the river system is used to control the flow entering the biological treatment. The corresponding WEST® model can be seen in Figure 3.

Results and discussion

Figure 4 shows the resulting ammonia concentration at the Station overflow location, with and without the control being active. It can clearly be seen that not in all cases the ammonia concentrations can be kept below the desired 1.5 mg NH_4-N/l, but the time that the system is above this curve is less than in the non-controlled case. The ammonia concentration exceeding the desired setpoint is not the consequence of a limitation of the control strategy, but is originating from an upstream, uncontrolled overflow. Hence, control in the sewer system could further optimise the water quality. Still the control strategy allowed us to decrease the maximum ammonia concentration in the river during the period under study from 2.5 to 2.2 mg NH_4-N/l.

Simulations have also shown that the performance of the control system is sensitive towards the aeration capacity of the treatment plant since this determines the ammonia concentration in the effluent. When the aeration capacity is insufficient during high loads, ammonia might be pushed through the treatment plant, together with the upstream pollution peak, causing a worse system performance than the base case. It is therefore important to only overload the treatment plant when the plant has sufficient aeration capacity, since otherwise the effect of the control strategy might be a deterioration of the river water quality due to the timing of the different pollution flows.

Conclusions

To obtain the best river water quality possible under some given conditions, the real time control of the integrated urban wastewater system is a promising option. When a fast, simultaneously simulating model can be used in this control strategy the river water quality might be used to determine the optimal setpoints of a control strategy that uses this river quality information, such as immission concentrations. Three problems in creating a fast simultaneous model have been discussed, and the chosen solutions have been outlined. A submodel of the RWQM1, together with well defined connectors between the different submodels has been used in order to address the problem of incompatible state variables of the current state-of-the-art models for each of the subsystems. To simplify the hydraulics, the Kosim approach to describe urban run-off and transport in the sewer system was used. For the river hydraulics, a CSTRs in series modelling approach was chosen. The problem of the different software packages was solved by implementing the three described models in the WEST® simulator.

The usefulness of this approach was demonstrated in a case study in the Tielt catchment. The sewer system and the treatment plant model were calibrated and validated during a previous study, while the river model must be considered to be a semi-hypothetical evaluation model. The control strategy based on an ammonia measurement in the river has shown to be able to decrease the peak ammonia concentration in the river, while the duration of exceedance of a certain threshold could be decreased. It can be concluded that this case study is proof of the principle that an integrated real time control based on a fast simultaneously simulating model is a valuable option in urban water management.

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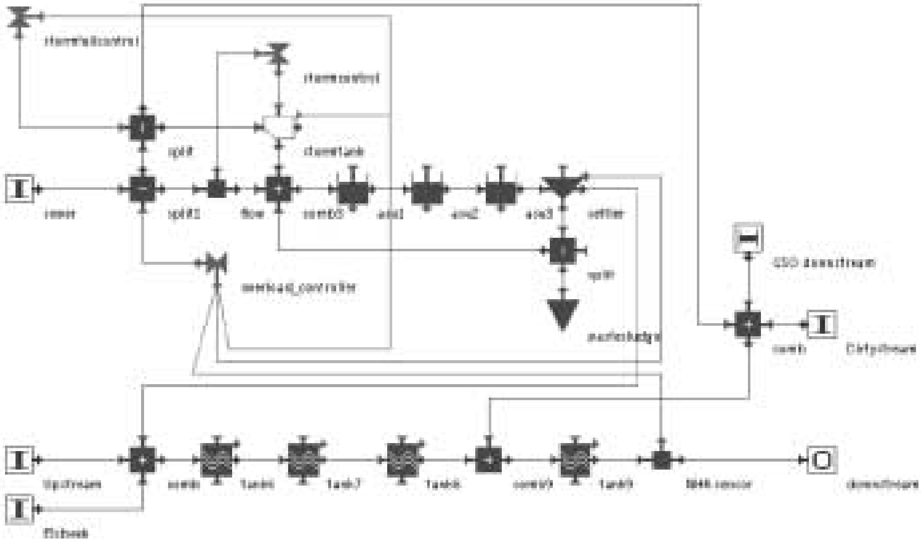

Figure 3 A simplified overview of the integrated model. Upstream and downstream elements have not been included for clarity

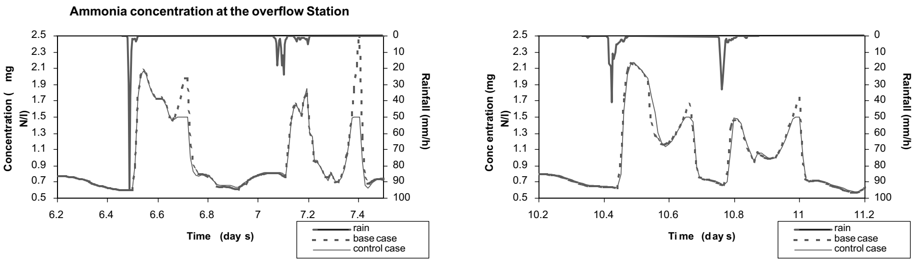

Figure 4 Simulated ammonia concentrations at the overflow station for the first and the second storm in the base case and the controlled case

References

Bauwens, W., Vanrolleghem, P.A. and Smeets, M. (1996). An evaluation of the efficiency of the combined sewer – wastewater treatment system under transient conditions. *Wat. Sci. Tech*., **33**(2), 199–208.

Beck, M.B. and Young, P.C. (1975). A dynamic model for DO-BOD relationships in a non-tidal stream. *Wat. Res.*, **9**, 769–776.

Carette, R., Bixio, D., Thoeye, C. and Ockier, P. (2001). Full scale application of the IAWQ ASM No. 2d model. *Wat. Sci. Tech.* **44**(2–3) 17–24.

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

Fronteau, C. (1999). Water quality management of river basins and evaluation of the impact of combined sewer overflows using an integrated modelling approach. PhD. Thesis, University of Brussels, Brussels, Belgium, pp 252.

Fronteau, C., Bauwens, W. and Vanrolleghem, P.A. (1997). Integrated modelling Comparison of state variables, processes and parameters in sewer and wastewater treatment models. *Wat. Sci. Tech.*, **36**(5), 373–380.

Gujer, W., Henze, M., Mino, T. and van-Loosdrecht, M. (1999). Activated sludge model No. 3. *Wat. Sci. Tech.* **39**(12), 183–191.

Hemmis, N.V., Koning Leopold III laan 2, B-8500 Kortrijk, Belgium. *http://www.hemmis.com/*.

Harremoës, P., Capodaglio, A.G., Hellstrom, B.G., Henze, M., Jensen, K.N., Lynggaard-Jensen, A., Otterhpohl, R. and Soeberg, H. (1993). Watewater treatment plants under transient loading – performance, modelling and control. *Wat. Sci. Tech.*, **27**(12), 71–115.

Henze, M., Grady, C.P.L., Gujer, W., Marais, G.v.R. and Matsuo, T. (1987). *Activated sludge model No. 1*. IAWQ, London, ISSN: 1010-707X.

Henze, M., Gujer, W., Mino, T., Matsuo, T., Wentzel, M.C. and Marais, G.v.R. (1995). *Activated Sludge Model No. 2, IAWQ*, London, ISSN 1025-0913, ISBN 1 900222 00 0.

Henze, M., Gujer, W., Mino, T., Matsuo, T., Wentzel, M.C. and Marais, G.v.R. and van Loosdrecht, M. (1999). *Activated Sludge Model No. 2d*. *Wat. Sci. Tech.*, **39**(1), 165–182.

Lessard, P. and Beck, M.B. (1990). Operational water quality management: control of storm sewage at a wastewater treatment plant. *J. Water Pollut. Control Fed*., **62**, 810–819.

Meirlaen, J., Benedetti, L., Sforzi, F., Facchi, A., Gandolfi, C. and Vanrolleghem, P. (in preparation a). Dynamic integrated modelling: a case study on the river Lambro.

Meirlaen, J., Sforzi, F., Benedetti, L. and Vanrolleghem, P. (in preparation b). The use of tanks in series models to describe hydraulic phenomena in rivers.

Meirlaen, J., Huyghebaert, H., Sforzi, F., Benedetti and Vanrolleghem, P.A. (2001). Fast, parallel simulation of the integrated urban wastewater system using mechanistic surrogate models. *Wat. Sci. Tech.* **43**(7) 301–309.

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

Pleau, M., Pelletier, G., Colas, H., Lavallée, P. and Bonin, R. (2001). Global predictive RTC of Quebec urban community's Westerly sewer network. *Wat. Sci. Tech.* **43**(7) 123–130.

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

Reda, A. (1996). *Simulation and control of stormwater impacts on river water quality*. PhD. Thesis. Imperial College London, UK. pp. 512.

Reichert, P., Borchardt, D., Henze, M., Rauch, W., Shanahan, P., Somlyódy, L. and Vanrolleghem, P.A. (2001). River water quality model no. 1 (RWQM1): II. Biochemical process equations. *Wat. Sci. Tech.* **43**(5) 11–30.

Schütze, M., Butler, D. and Beck, B. (1998). Optimisation of control strategies for the urban wastewater system – an integrated approach. *Wat. Sci. Tech.*, **39**(9), 209–216.

Shanahan, P., Borchardt, D., Henze, M., Rauch, W., Reichert, P., Somlyódy, L. and Vanrolleghem, P.A. (2001). River water quality model no. 1 (RWQM1): I. Modelling approach. *Wat. Sci. Tech.* **43**(5) 1–9.

Takacs, I., Patry, G.G. and Nolasco, D. (1991). A dynamic model of the clarification-thickening process. *Wat. Res.*, **25**, 1263–1271.

Taylor, S., Williams, W., Murrell, K. and Berislav, T. (2000). Status and development plans for the integrated catchment simulator. *In: Proceedings of the IMUG2000 conference*. Prague, Czech Republic, April 12–14, 2000.

Van Assel and Dierickx, M. (2000). Integrated modelling of the Tielt and Poekebeek catchment. *In: Proceedings of the IMUG2000 conference.* Prague, Czech Republic, April 12–14, 2000.

Vanrolleghem, P.A., Schilling, W., Rauch, W., Krebs, P. and Aalderink, H. (1999). Setting up measuring campaigns for integrated wastewater modelling. *Wat. Sci. Tech.*, **39**(4), 257–268.

Vanrolleghem, P.A., Borchardt, D., Henze, M., Rauch, W., Reichert, P. Shanahan, P. and Somlyódy, L. (2001). River water quality model no. 1: III. Biochemical submodel selection. *Wat. Sci. Tech.* **43**(5) 31–40.