Integrated modelling as an analytical and optimisation tool for urban watershed management

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Abstract In recent years numerical modelling has become a standard procedure to optimise urban wastewater systems design and operation. Since the models were developed for the subsystems independently, they did not support an integrated view to the operation of the sewer system, the wastewater treatment plant (WWTP) and the receiving water. After pointing out the benefits of an integrated approach and the possible synergy effects that may arise from analysing the interactions across the interfaces, three examples of modelling case studies carried out in Germany are introduced. With these examples we intend to demonstrate the potential of integrated models, though their development cannot be considered completed. They are set up with different combinations of self-developed and commercially available software. The aim is to analyse fluxes through the total wastewater system or to integrate pollution-based control in the upstream direction, that is e.g. managing the combined water retention tanks as a function of state variables in the WWTP or the receiving water. Furthermore the interface between the sewer and the WWTP can be optimised by predictive simulations such that the combined water flow can be maximised according to the time- and dynamics-dependent state of the treatment processes.

Keywords Integrated modelling; real-time-control; receiving waters; urban drainage; WWTP-Online-Simulation

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Introduction

Today's planning guidelines deal with the individual urban wastewater components of sewer system, wastewater treatment plant (WWTP) and receiving water separately, i.e. they are designed and operated as independent components. An integrated view of these subsystems is implicitly introduced by the recent Water Framework Directive (WFD; EU, 2000). The goal set in the directive is to reach a good ecological status of all water bodies throughout the catchment, rather than prescribing certain design rules. Water protection policies conform with the WFD aim of optimising river basin management in both ecological and economic regards. This cannot be achieved with the management approach adopted to date, that is based on discharge standards for individual point sources not considering the impact from any other discharge point. Therefore, sustainable river basin management can only be established by adopting an integrated approach based on receiving water criteria. Numerical models are important tools to analyse existing systems, the water flows and matter fluxes between the subsystems and to develop optimisation strategies to reduce the total impact on the receiving water from the sewer system and WWTP.

Until now numerical models have been developed independently for the different parts of urban wastewater systems. As a consequence the numerical models, as well as the simulation software, have been incompatible at the subsystems interfaces. Under this condition, it is impossible to simulate the processes in the subsystems in parallel, which is a prerequisite to model integrated real time control, i.e. take control actions in the sewer system based on the operational state of the WWTP. Moreover, the option to implement integrated online simulation is needed to perform predictive simulations. This can be applied to e.g. estimate the maximum stormwater inflow that can be treated in the WWTP, based on the description of the current status of the WWTP processes, that is identified by an online observer model supported by measurements.

In this paper we give an overview on the capacity of integrated operation and/or simulation by introducing three projects presently carried out in Germany.

Overview of integrated modelling projects

Sequential and parallel modelling are the two conceptual approaches of integrated modelling. In sequential modelling, the simulations of the subsystems are performed sequentially and decoupled. The output data of the upstream sub-model (e.g. sewer system) form the input data for the downstream sub-model (e.g. WWTP). The river quality model is fed by discharge data of CSO and WWTP, including flow-rate and matter-load information. No feedback to the upstream sub-models is provided. In parallel modelling, all components of the urban drainage system are simulated simultaneously. This procedure offers major advantages in cases where a system feedback is necessary. The prerequisite for these simulations is to provide reliable model interfaces interconnecting the sub-models. This is only fulfilled in "open simulation systems" (e.g. Rauch and Harremoës, 1998; Schütze, 1998; Alex *et al.*, 1999).

Table 1 shows a compilation of some integrated modelling studies and their features. The broad range of application goals and the variety of used and developed simulation tools in the four subsystems (catchment surface, sewer system, WWTP, receiving waters) are indicated, as well as the information on the software platform and on the sequential or parallel coupling of the subsystems.

Different application examples

In the examples introduced in the following, the primary objectives were to optimise the operation of the total system and to reduce the impact on the receiving waters. They cover different types of implemented models, of coupling approaches and particularly of application: i.e. in the offline mode for decision support or in the online mode for model-based predictive control.

Example 1: vase study Odenthal, Germany

Most of the commercially available software packages are closed systems and cannot be modified or further developed by the user. Since this is an important aspect in a rapidly developing field (e.g. in-sewer pollutant conversion models or river water quality models) the general purpose and open simulation platform MATLAB® SIMULINK® (Figure 1) was chosen as the model base (see e.g. Alex *et al.*, 1999). This platform allows implementation of general or site-specific real-time-control (RTC) algorithms developed by the user in integrated models (Risholt *et al.*, 2001). An advantage of SIMBA® sewer and SIMBA®, the software for sewer and WWTP modelling, respectively, running on the MATLAB® SIMULINK® platform is that they allow implementation of user-defined conversion models in a matrix-oriented form (see Henze *et al.*, 1987).

The integrated model was applied to optimise the wastewater system of Odenthal. The Odenthal sewer system (Figure 2) has a simple dendritic structure with three branches, four combined water retention tanks (RUB) and 5 CSO structures (RU). Combined sewers drain the major part of the system. The sewer simulation includes transport processes for water and pollutants (dissolved COD, particulate COD and ammonia), of which only the models for flow and sedimentation/erosion of particulate COD are currently used. The largest

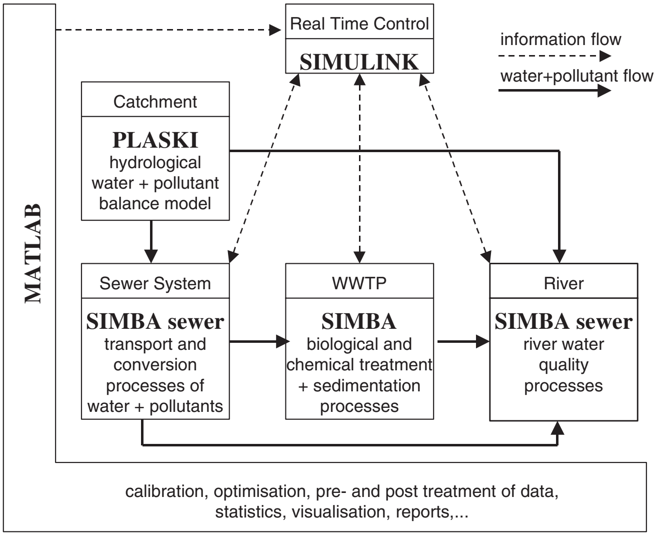

Figure 1 Simulation environment for integrated modelling

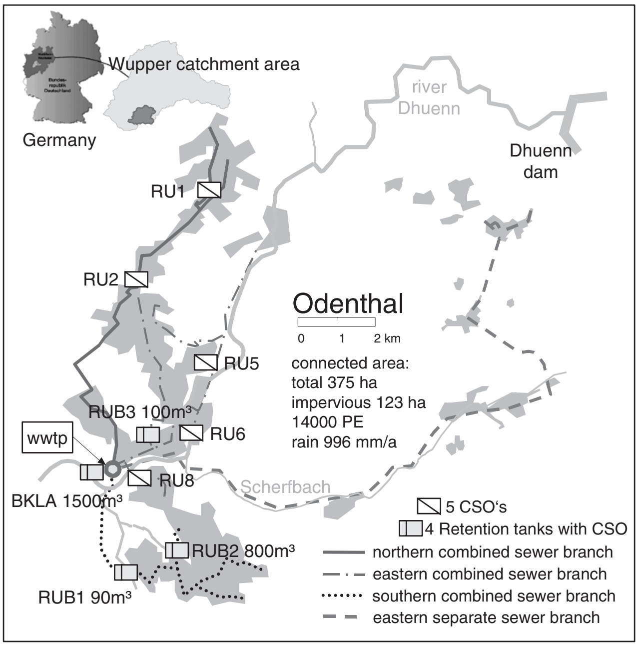

Figure 2 Odenthal wastewater system

retention tank (BKLA) is located next to the WWTP, that is a two stage activated sludge system. The plant is designed for nitrogen removal and simultaneous phosphate precipitation. The biological processes are modelled with ASM1 (Henze *et al*., 1987) while for secondary clarification a one-dimensional approach is used (Otterpohl, 1995). The main receiving water in the catchment is the river Dhuenn, which has a near-natural morphology and should thus be protected from pollution impacts. A 14 km reach of the Dhuenn from Odenthal to the mouth is simulated with a submodel of the RWQM1 (Reichert, 2001) which describes conversion processes for dissolved nitrogen and phosphorous compounds based on the assumption of constant concentration of biomass and algae.

Table 1 Integrated modelling studies and their features

Author	Area	Aim	Surface runoff model	Sewer system	WWTP	River
Dudley, Tomicic (1998), Mark, Williams (2000)	(general)	EU-Project: optimisation of data transfer between the used models (real-time system).	MOUSETRAP		STOAT (ASM1 + 2; SST Takacs)	MIKE 11
Lindberg *et al.* (1999)[x]	Helsingborg, Denmark	Same EU-Project: Development of a tool for RTC. Parallel modelling in preparation with ICS	Integrated Catchment Simulator (ICS) MOUSE-TRAP (Q, solved components)		(STOAT) in preparation	(MIKE11) in preparation
Erbe (2000), Risholt *et al.* (2001)	Odenthal, Germany	Optimisation of river water quality with RTC in sewer system and WWTP.	PLASKI (COD fil+tot, NH_4-N)	SIMBA® sewer (transport, not calibrated for sediments) Matlab®/Simulink®	SIMBA® ASM1, SST 1d OF	RWQM1 (in preparation)
Frehmann *et al.* (2001)	Bochum, Germany	Optimisation of river water quality with RTC in sewer system	MOSI	SIMBA®sewer Matlab®/Simulink®	SIMBA® (ASM1)	AQUASIM
Hansen, Leinweber (1999)	Eschringen, Germany	Integrated process control of sewer + WWTP, regarding total emission of COD, NH_4-N, Q	KOSMO (incl. settling process in the tanks)		SIMBA® (ASM1)	No regard
Holzer, Krebs (1998)	Bauma, Switzerland	Evaluating different structures in sewer system, regarding NH_4-N, dynamics in single events	MOUSE TRAP (only Q & NH_4-N)	AQUASIM	ASM1, own model PST+SST	AQUASIM
Milina *et al.* (1999)	Trondheim-Hoevringen, Norway	Optimising cost-efficiency of system extension before upgrading the WWTP. Single events + long-term				
Risholt (2000)	Fredikstad/ Oslo, Norway	Determination of the river pollution + the potential to minimise the load with RTC. Long-term; P_{tot}	PLASKI	SIMBA®sewer Matlab®/Simulink®	SIMBA®	No regard
Rauch, Harremoës (1996)	semi-virtual, Denmark	Analysis of the decisive load constellation for oxygen depletion in receiving waters	Deterministic integrated model with simplified approaches. No regard of the material conversion in the sewer			
Van der Roest *et al.* (1998)	Harderwijk & Tholen, Netherlands	Optimal use of the existing infrastructure, minimise investment and operational costs => Consider the system and dynamics entirety.		NWRW (NH_4-N, SS, Q) RITZ	SIMBA®	No regard
Meirlaen *et al.* (2001)	Lambro, Italy	Development of a surrogate model for a fast, parallel simulation to take the river water quality into account, model based predictive control.	– WEST® simulator with surrogate models or connection to ASM + RWQM1	–	ASM1	RWQM1
Schütze (1998)	Semi-hypothetical, Norwich	Case studies to examine advantages of the integrated view and control as compared to the conventional approach.	KOSIM integrated: SYNOPSIS		ASM1	DUFLOW
Seggelke, Rosenwinkel (2000)[x]	Hildesheim, Germany	Optimise the inflow into the WWTP by online-simulation of the WWTP to reduce the total emission. Single events + long-term	KOSIM		SIMBA® ASM2d	(RWQM1) in preparation

([x] Sequential Simulation; grey shaded: examples from the authors, introduced in this paper)

The set-up of the interfaces between the submodels is particularly important. For the interface sewer-WWTP the 3 pollutants simulated in the sewer-model are fractionated into the 13 fractions of ASM1 by using standard parameters for ASM1 inflow fractionation of COD and ammonia. A similar concept is used for the interface sewer-river. As the model concept of RWQM1 is similar to that of ASM1, the definition of the interface WWTP-river did not require special conversion. It is planned to implement a sewer quality model that is based on a ASM1-like concept as proposed by Almeida (1999) in order to have a similar set of pollutants in all submodels.

There are several reasons why the Odenthal system is examined by applying the integrated approach. Firstly, the WWTP does not meet the German effluent standards for nitrogen concentration. Secondly, the transition from dry-weather to wet-weather loading is to be smoothed as the respective difference is high, while thirdly, the CSO discharges to the receiving waters are not to be increased.

The simulations of the integrated system were carried out in a first step to understand the various substance flows in the system, e.g. the pollution loads from the three main subcatchments or the sensitivity of the river to CSO at the different discharge sites. In a second step, control strategies were applied to integrate the system. As a result it can be stated that it is most effective to increase the combined water load to the WWTP based on the continuously estimated nitrification capacity, in combination with controlling the operation of the largest combined-water retention tank in the sewer system.

Example 2: case study "Schattbach" in Bochum, Germany

An urban catchment situated in the south-east part of Bochum, Germany, is used to investigate the interaction of the wastewater subsystems by means of an integrated modelling approach. The catchment called "Schattbach" exhibits a total size of 3.67 km^2, of which approximately 1.67 km^2 is impervious. The settlement structure consists of residential buildings (approximately 15,000 Inh.) with light industry and one large factory. The average annual rain depth amounts to approx. 850 mm/a. The catchment is drained by a combined sewer system comprising four retention facilities with a total storage volume of approximately 11,000 m^3. The dominant facility is an inline storage sewer just upstream of the biological WWTP with preliminary denitrification. CSOs are discharged into the "Schattbach" creek, a heavily modified water body that will be re-naturalised. Accordingly, the simulations are carried out assuming the re-naturalised planning state of the "Schattbach".

The output parameters of the sewer (in terms of CSO loads) and the WWTP model are used to characterise the impact on a simplified river quality model. The impact on the receiving water is quantified by means of three indicators: bottom shear stress, oxygen deficit and ammonia concentration. The comparison of the effects of the different cases was carried out for a summer period from 13.07.1998 to 16.09.1998. During this period, 17 rain events were continuously recorded by five rain gauges, while 9 rain events led to overflows. Moreover, water levels and flow rates were measured at different locations in the sewer system. For all CSO events, the overflows into the receiving water were sampled by automatic devices and analysed in the laboratory.

By linking the four individual subsystems models into one integrated model in which the processes in the subsystems are operated in parallel, the total pollution load to the receiving water resulting from CSOs and the WWTP effluent can be examined. Critical cases were defined to quantify the impact of control measures on the water quality in Schattbach. For the simulation of the runoff from the catchment surface, the surface runoff model MOSI was developed on the platform MATLAB®/ SIMULINK®, using hydrological approaches (Frehmann *et al.*, 2001). The simulation of flow and pollutants transport within the sewage network and the retention facilities was performed with the program SIMBA®sewer. The modelling of the free surface flow is described through the diffusive wave approximation of the St. Venant equation system. The software SIMBA® is used to simulate the processes in the biological WWTP on the basis of ASM1 (Henze *et al*., 1987). The receiving water was simulated using the software package AQUASIM (Reichert, 1994) with the modelling concept of Niemann (2000).

The flow rate in the sewer system was managed by controlling the outflows of the retention facilities. An integrated control was implemented in the model to adjust the outflows depending on the relative water levels in the retention facilities. The target was to produce simultaneous overflow from all three retention devices, adjusting the outflow rate directly in proportion to the difference between the local relative filling degree level and the average relative filling degree. Figure 3 shows the flows through the WWTP and discharges into the receiving water via CSOs during the examination period of 66 days; PS stands for present situation, RTC for real time control in the sewer system and RIA for reduction of impervious area feeding the sewer system. By controlling the outflow from the retention volumes (RTC), the CSO discharge to the receiving water is reduced by 12% and so is the respective COD load. In the option RIA, the impervious area in the catchment was reduced by 10%, resulting in a CSO discharge reduction of 32%. Thus, volume activation in the existing tanks may diminish the discharge frequency into the receiving water considerably. The effects of these particular measures are less relevant regarding the quality parameters COD and NH_4-N. For example the reduction by RTC is only about 5% for COD and by RIA about 14% (Figure 4).

In contrast to this, hardly any reduction of the maximum discharge concentration either of COD or of ammonia could be achieved. However, one has to consider that for the simulation of the pollutants concentration in the sewer system a conservative approach is used which does not consider sedimentation and bio-chemical processes in the sewer system. A full description of the impacts on receiving water quality can be found in Frehmann *et al*. (2001).

Example 3: model-based predictive control, WWTP Hildesheim, Germany

Example 3 is an on-going research project, financed by the German Ministry (BMBF), in which the potential of online-application of integrated modelling is examined. The aim is to make optimal use of the WWTP capacity during storm events, i.e. to increase the combined water inflow to the WWTP beyond the double dry-weather peak flow typically allowed, while still meeting the effluent standards. Since the spare treatment capacity is event-

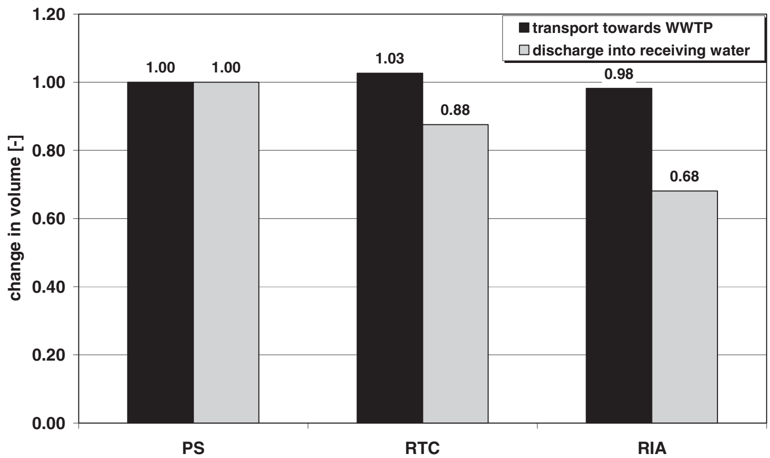

Figure 3 Comparison of transport towards WWTP and discharge into receiving water

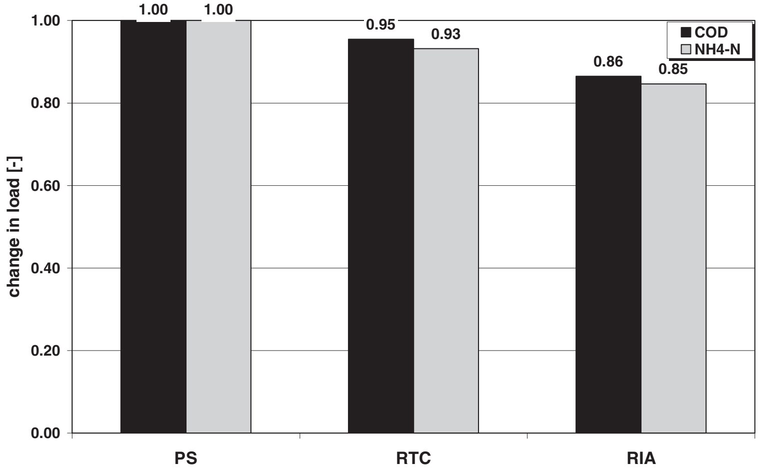

Figure 4 Comparison of COD and NH_4-N load into receiving water

dependent, a monitoring system, based on a model-based adaptive prediction, is implemented. This allows the determination of the optimal control strategies of the treatment processes and the maximum inflow. Therefore, the WWTP model (ASM2d, SIMBA®) is coupled with the sewer model (KOSIM).

The main information on the catchment is described in Table 2. The following parameters were measured online over a period of up to 2 years: flow rate to the WWTP and into the receiving water from each CSO structure, turbidity, SAC in one overflow discharge, flow rate and various compound concentrations in the influent and effluent of the WWTP and in the river Innerste (e.g. NH_4-N, NO_3-N, O_2). These measurements were used for model calibration and verification. The verification according to the data of more than a half year period turned out very satisfactory.

Figure 5 shows the structure of the adaptive predictive approach as it has been installed for some months so far. The WWTP prognosis model is fed with results from KOSIM, that is loads in the inflow, and from the online observer model, that gives the actual state of the biological process. Based on these inputs, the WWTP effluent quality can be predicted continuously for various loading scenarios and allows estimation of the maximum possible inflow, and to choose the optimal control strategy for the WWTP operation in case of combined water inflow. Details on the model, the prerequisites for the online implementation (i.e. fractionation, influent generation) and the WWTP control strategies can be found in Seggelke and Rosenwinkel (2000).

The analysis of the first simulation and prognosis results, also with regard to the reliability of this practical application, is presently in progress. Thus, the tool has not yet been applied to control the real WWTP processes.

Beyond this, case studies under various storm water conditions and different inflows to the WWTP with regard to the interactions between the subsystems and the resulting emission

Table 2 Information on the area

Catchment area	870 ha impervious
Inhabitants:	110,000 Inh, WWTP: 240,000 P.E.
Rainfall high	580 mm/a
Sewer system (design: ATV A128)	Hydraulic separate areas each with CSO predominantly: combined system; 11 CSOs
WWTP (design: ATV A131)	Aeration tank with circulation flow, EBPR
Receiving water	Innerste, $Q = 8\ m^3/s$

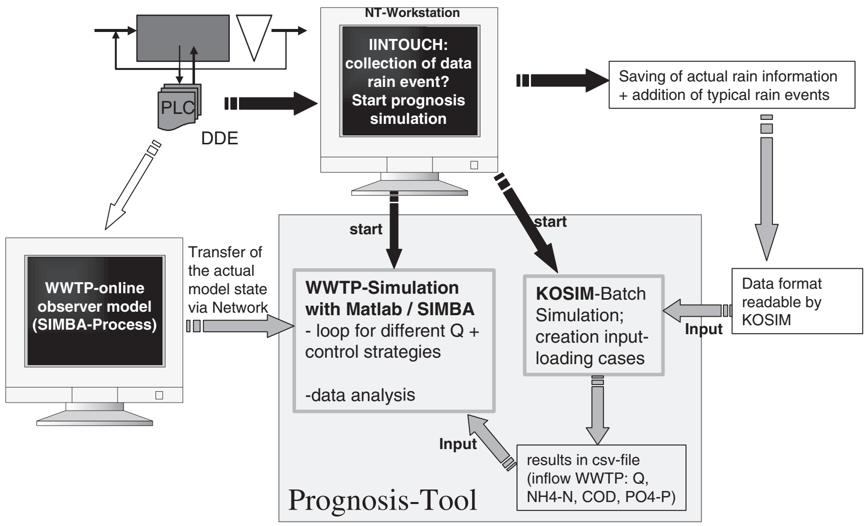

Figure 5 System of the online-simulation with prediction

will be carried out. After the test period the sewer model SIMBA® sewer and the IWA river water quality model (RWQM1) should be integrated with the predictive WWTP tool on the common basis of MATLAB®/SIMULINK® for parallel coupling of the subsystems models.

Difficulties in integrated modelling

The main difficulties in integrated modelling are: uncertainties in the input data and the description of ongoing processes, lack of calibration data, handling and linking of the single models into an integrated model and often the missing acceptance by the authorities.

While modelling of the hydraulic processes in the submodels is generally successful, the description of the water quality processes in sewers is still uncertain, whereas it is much more advanced for processes in the WWTP and the river. In conventional sewer models, the pollutant concentrations are often assumed equal in all runoff events and constant over their duration, which is an obvious shortcoming.

For the practical application of integrated models, calibration and verification with measured data is necessary. Usually, the hydraulic and quality part of each sub-model should be calibrated independently. However, the available data base for all components of the wastewater system is rather limited due to the enormous effort and costs necessary for adequate measurement campaigns. For this reason, conceptual models with simplified approaches are often applied for simulation.

The linking of the sub-models was a serious problem in the early years of integrated modelling. The main problem is that the simulated quality parameters are not the same in the sub-models, because in most cases the individual model components work with different quality parameter sets. Thus, at the interface the quality parameters must be converted to the set of the neighbouring sub-model. Since with this conversion information or accuracy may be lost, the development of harmonised parameter sets, relevant for all sub-models, is urgently needed.

The lack of acceptance by the authorities is mostly a result of regulations that do not acknowledge system integration, unrecognised potentials of integrated operation and modelling and the complexity of the approach. The latter is also the reason why integrated models can only be successfully applied (in terms of planning and approval) by highly experienced personnel. New users must acquire the skills by intensive training. This increases the costs as compared to modelling focusing on one subsystem.

Conclusions

With regard to optimising the design and the operation of the total wastewater system consisting of the sewer system, the WWTP and the receiving water, integrated modelling exhibits clear advantages as compared to the widely applied models of the subsystems. The interactions between the subsystems are considered and so is the fact that an improvement in one subsystem causes a decrease of the performance in the neighbouring subsystem. The goal of operation of the wastewater system, that is optimising the water quality in the receiving water, can only be reached by understanding the sewer system and the WWTP as a whole.

The three examples introduced in this paper and other case studies described in the literature identify the treatment of the interfaces as a common problem. On the one hand, the characterisation of wastewater or water quality, respectively, is different in the subsystems and must be converted at the interfaces with either loss of information or added uncertainty. On the other hand, the interfaces must be defined appropriately to run the models either in the sequential or in the parallel mode, meaning that the simulation of the processes in all three subsystems is run at the same time. Only the parallel mode is suitable to introduce integrated control options such as performing measurements in the WWTP or the receiving water and taking control actions in the sewer system.

With the case studies introduced in the paper it can be shown that integrated modelling can be used to analyse compound fluxes through the wastewater system, to compare the performance of various options in extending the system, to evaluate the performance of integrated control, and to make use of information from sewer and WWTP observer modelling to predict the effluent quality under various loading scenarios some hours ahead to determine the maximum possible inflow to the WWTP during wet-weather conditions. The promising results obtained so far in the modelling studies should be evaluated after they have been tested in the real systems in the future.

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