

Effects of real time control of sewer systems on treatment plant performance and receiving water quality

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Abstract Four individual mathematical submodels simulating different subsystems of urban drainage were intercoupled to an integral model. The submodels (for surface runoff, flow in sewer system, wastewater treatment plant and receiving water) were calibrated on the basis of field data measured in an existing urban catchment investigation. Three different strategies for controlling the discharge in the sewer network were defined and implemented in the integral model. The impact of these control measures was quantified by representative immission state-parameters of the receiving water. The results reveal that the effect of a control measure may be ambivalent, depending on the referred component of a complex drainage system. Furthermore, it is demonstrated that the drainage system in the catchment investigation can be considerably optimised towards environmental protection and operation efficiency if an appropriate real time control on the integral scale is applied.

Keywords Combined sewer overflow; integral model; real time control; receiving water; water quality modelling

Introduction

Today planning standards deal with the individual urban drainage components (sewer system, wastewater treatment plant (WWTP) and receiving water) separately, i.e. they are dimensioned and operated as single components. In contrast to this, an integral handling considers the drainage components intercoupled. This novel approach allows a holistic and more sustainable planning of urban drainage systems. In accordance with this development, the recent EU Water Framework Directive requires water management measures to be related to the local catchment area. In this paper, potentials for ecological and economic optimisation of an existing urban catchment drainage are presented based on a model case study.

Examined topics and area description

An urban catchment area in the south-east part of Bochum, Germany is used to investigate the interaction of the individual drainage components by means of the integral modelling approach. The catchment called "Schattbach" exhibits a size of total 3.67 km², of which approximately 1.67 km² are impervious. The settlement structure consists of residential buildings (approximately 15,000 Inh.) with light industry and one large factory. The average rain load is at approximately 850 mm/a. The catchment area is drained by a combined sewer system comprising four treatment facilities with a total storage volume of approximately 11,000 m³. The dominant facility is an inline storage sewer downstream of which the wastewater is treated by a biological WWTP with preliminary denitrification. Water discharged from CSO is diverted into the "Schattbach" creek, a receiving water converted into an open denatured channel. In future the natural watercourse network is to be restored by integrating "Schattbach" into the landscape as a flow course. Accordingly, a fictitious planning state of the "Schattbach" is assumed in the following.

By coupling three separate mathematical models (sewer system, WWTP and receiving water) into one single model, the total pollution load of the receiving water resulting from CSO and the effluent of the WWTP can be examined. Three different cases were defined to quantify the impact of control measures on the water quality in Schattbach (see Table 1). The current state (case 0) corresponds to a maximum throttle outflow of the twice daily dry weather flow ($2 Q_d$) to the WWTP whereas this value was increased to $5 Q_d$ for case 1. For case 2, the available retention volume was more extensively utilized by a flexible regulation of throttle discharge. In all cases, the throttle discharge to the WWTP is limited by a gate coupled to a flow measurement device (MID). The test cases are listed and described in Table 1.

The following input parameters are provided to a simplified river quality model: the outflow of the WWTP and the CSOs (randomly discharged from the sewer system). They are obtained as output parameters of the respective submodels. The impact on the receiving water is quantified in all cases by means of three indicative parameters: bottom shear stress, oxygen deficit and ammonium 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, a total of 17 rain events were continuously recorded by five rain gauges, with 9 rain events leading to CSO activity. Moreover, water levels and discharges at different locations in the sewer system were measured as well. For all discharge events, the overflows into the receiving water were sampled by means of automatic devices and analysed in the laboratory with respect to quality parameters.

Development of integral modelling approaches for planning of drainage system

The development and application of models for drainage system planning is currently in a state of change. One result of the first INTERURBA Workshop (Lijklema *et al.*, 1993) was the thesis that a measure does not necessarily improve the performance of the entire drainage system. The effect is rather dependent on the drainage system component taken as reference (sewer system, WWTP or receiving water). Consequently uniform, integral modelling concepts have been required. Thus, model-based integral concepts have been created in Europe primarily outside of Germany. Particularly in recent times, several authors successfully presented integrated models for the analysis and optimisation of the drainage systems (i.e. Rauch, 1995; Schütze, 1998). In Germany, this development proceeds to a limited extent and e.g. the immission analysis of the component “receiving water” has been often neglected.

One major feature of integrated modelling concepts is the explicit emphasis of the component “receiving water”. If not considered the resulting conclusions may even become counterproductive for the drainage system optimisation. (Rauch and Harremoës, 1998). Two conceptual approaches can be distinguished in modelling the entire system: sequential modelling and parallel modelling.

In the sequential modelling, the calculation is done in sequence decoupled for the individual components. The output data of the preceding submodel (e.g. sewer system) form the input data for the following submodel (e.g. WWTP) The river quality model is fed by

Table 1 Examined scenarios of the Case Study

No.	Name	Control measure	Control quantity and control location
0	current state	Local RTC	throttle discharge at the last tank = $2 Q_d$
1	increased throttle discharge	Local RTC	throttle discharge at the last tank = $5 Q_d$
2	retention volume control	Global RTC	water level control in all 3 tanks and throttle discharge at the last tank = $2 Q_d$

discharge data of CSO and WWTP. No feedback between the submodel is provided and program interfaces for handling of data formats must be programmed.

In the parallel modelling, all components of the urban drainage system are calculated simultaneously. This procedure offers crucial advantages in cases of system feedback (e.g. between the receiving water and sewer system). The prerequisite for these calculations is the provision of reliable model interfaces interconnecting the submodel in real time. This is fulfilled only in “open program systems” (e.g. Rauch and Harremoës, 1998; Schütze, 1998; Alex *et al.*, 1999).

Integrated model for the drainage area “Schattbach”

For the integrated simulation of sewer system, WWTP, and receiving water, it is necessary to couple the individual models to one another. In this study, a total of four different single models were coupled into one integral parallel model. Figure 1 shows the developed integral model for the catchment area Schattbach. The two system components “diffuse loads” and “interaction with groundwater” were not incorporated into the integrated model; they are considered through lump assumptions. For instance, the diffusive load from the surface is considered by setting a conservative assumption of the background concentration of substances during wet-weather events.

Model components for the integral calculation of the entire system

For the simulation of the runoff from the surface, the surface runoff model MOSI was developed at the University of Essen on the platform MATLAB[®]/SIMULINK[™], using hydrological approaches (Frehmann *et al.*, 2000). The surface runoff is modelled using linear storage cascades. The infiltration losses at natural surfaces are modelled with the SCS method. To calculate the pollutant concentration in the surface runoff, one can choose between a constant surface runoff concentration, which is calculated from the annual rainfall and the substance potential (3-component method), and an approach which considers the substance accumulation and the erosion at the surface. Input data for the simulation are measured rainfall, as well as the daily characteristics for domestic and industrial wastewater productions, if available. The conveyance of the discharge and pollutants within the sewage network and the facilities for rainwater treatment were calculated with the program SIMBA[®]sewer (Ifak, 1997), which works on the basis of MATLAB[®]/SIMULINK[™]. The

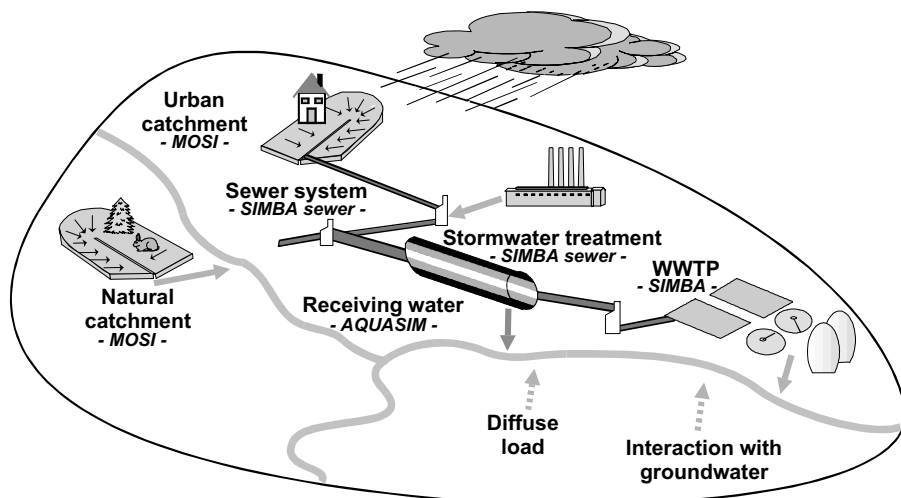


Figure 1 Integrated model system for the drainage system area “Schattbach”

modelling of the water transport is described through the diffusion wave approximation of St. Venant's equation system as a hydrodynamic model. With this model, an "unlimited" number of substances (dissolved or solid) can be simulated. Approaches for sedimentation, chemical and biological processes in the drainage system can be freely implemented by the user. The software package SIMBA® (Ifak, 1997) is used to calculate the biological WWTP. By now this software has become de-facto a standard for dynamic WWTP simulation in Germany. The plant with preliminary denitrification is simulated based on the model concept ASM 1. The part model was calibrated using measured data and test results (Niemann and Orth, 2000). The receiving water was simulated using the software package AQUASIM (Reichert, 1994).

Example: simulation of the water quality modelling approach in the integral model

The selected modelling concept for the receiving water aims primarily at the evaluation of the acute pollution load. The model does not consider individual processes in the catchment in the natural complexity but rather simulates the dominant ones as simplified as possible. A complete description of the model concept and of the current status of water quality modelling approaches can be found in Niemann (2000). The applied model structure is described in the process matrix (Table 2).

All biological processes in a given receiving water section take effect on the oxygen mass-budget. In the calculation, ammonium is regarded as a conservative substance which is not subject to any nitrification and thus causes no oxygen consumption. This assumption is tolerable for the specific scenarios since short-term ammonium availability does not lead to any significant growth of autotrophic biomass and the dry weather concentrations of ammonium in the receiving water are low. At background concentrations lower than 0.3 mg NH₄-N/l, hardly any nitrifiers can survive in the system (Jancarkova, 1999). Due to the lack of measured data the degradation constants for the carbon conversion (COD reduction) were taken as reference values. We distinguished between the degradation during the stormwater discharge and the delayed degradation after sedimentation, because the delayed oxygen consumption in the receiving water is crucial for the oxygen budget

Table 2 Process matrix of the water quality model applied in the integrated modelling (Niemann, 2000)

variable	i	1	2	3	4	5	Rate
J process		S _S	X _D	X _D *	S _{O2}	SNH	[g/(m ³ d)]
1 reaeration					1		K ₂ (O ₂ ,sat-O ₂)
2 photosynthesis					1		P/y
3 respiration					-1		R/y
4 deoxygenation of COD		-1			-1		K ₁ S
5 sedimentation of COD			-1	1			w/y X _D
6 delayed deoxygenation (COD) on the streambed				-1	-1		K ₄ X _D
oxygen saturation according to McCutcheon (Epa, 1989)							parameters: K1: degradation rate for COD (1st Order) (0.5 [1/d]) K2: reaeration coefficient Wolf (1974) [1/d] K4: degradation rate on the bed surface (2.5 [1/d])
y: effective water depth [m]							
P: photosynthetic production rate in g O ₂ / (m ² d)							
R: respiration rate [6.5 g O ₂ / (m ² d)]							
w: sedimentation [1.5 m/d]							
		soluble, rapidly degradable organic matter [g COD /m ³]	part., slowly degradable org. matter [g COD /m ³]	part., slowly degradable org. matter [g COD /m ²]	oxygen	Soluble Ammonium [g NH ₄ -N /m ³]	

(Hvitved-Jacobsen and Harremoës, 1981). From the simulation of the WWTP treatment performance, according to the ASM concept in the simulation of WWTP the discharged COD is conceptually subdivided into substance fractions. The water quality model distinguishes between easily degradable substances (i.e. dissolved organic substances, S_S), slowly degradable substances (i.e. in particulate form, X_D) and inert substances (i.e. subject to no degradation, X_I). For simplicity, the simulated COD both in the CSO discharge and in the surface runoff was assumed to be the same as the raw-water fractionation (measured at the inlet to WWTP and used for the WWTP simulation). This fractionation was considered to be temporally constant due to the lack of any measured data ($S_S = 20\%$; $S_I = 5\%$; $X_S = 55\%$; $X_I = 20\%$ – in accordance with ASM 1). In an integrated model, oxygen concentrations must be given for all discharges into the receiving water. This is done by a simplified lump assumption of 80% oxygen saturation. This assumption is permissible, as the O_2 -content in the discharges is largely determined by turbulent flow conditions.

Immission based parameters as limit/target values in the receiving water

For the evaluation of the various measures the crucial emission parameters are compared to the immission reference parameters. The current impact of the immissions from the operating part systems “sewer system” and “WWTP” can be evaluated using the water quality simulation coupled therewith. Then, the relevant immission-related target and limit values must be formulated accordingly for the overall conditions in the receiving water. Using the example of a lowland river, the possible limit values for the main immission load parameters could be: bottom shear stress ($\tau_{crit} = 10 \text{ N/m}^2$), ammonia toxicity ($0.1 \text{ mg NH}_3/\text{l}$) and oxygen deficit ($4 \text{ mg O}_2/\text{l}$). Other limit values, particularly of the dynamic type in dependence on the exposition time, are also possible, but not used in this case study. “Urban Pollution Manual – UPM” (FWR, 1998) lists ecotoxicologically verified criteria (LC_{50}) for quantification of acute pollution in running waters. For simplicity the formulated target values based on threshold values which have not been ecotoxicologically verified.

Application of the integrated model for pollutant flow analysis and system optimisation of the drainage components

For the integrated approach, first the single models were calibrated and verified, and then incorporated into a coupled model. For instance, the surface runoff model and the transport model for the sewer system were calibrated and verified with respect to substances and hydraulic conditions using more than 20 independent events. Niemann and Orth (2000) approved the model for the WWTP in a semi-technical pilot plant. The calculation of the surface runoff, the transport in the sewer system, and the treatment in the WWTP ran parallel. The effluent from the WWTP and the CSO are subsequently used as input data for the sequential simulation with the river quality model. In the current constellation, the four single systems are not only operated completely separated from each other, but the single systems are controlled only by local measures. For instance, at the outflow of the last inline storage sewer before the WWTP there is only a standalone gate controlled by a MID. There is no combined control i.e. no feedback from the conditions in other storage tanks.

Impact of a throttle variation

In case 1, the throttle effluent is increased from originally $2 Q_d$ to $5 Q_d$. This measure leads to increased water amounts flowing to the WWTP and results in different total emissions. The WWTP particularly has a limited reception capacity. Thus, in case of stormwater inflow, the activated sludge is displaced to the secondary clarifier, and from there out of the

WWTP if the hydraulic load is too high. The acute impacts of the WWTP operation for throttle limit of 2 and 5 Q_d were quantified exemplarily using the two-peak rainfall event from 26.08.1998 (Figure 2).

The rainfall event can be divided into two stages, an initial rain at about 12:00 with only low river flow rate ($< 1 \text{ m}^3/\text{s}$) and a main rain with a discharge from the inline storage sewer at about 16:00. The maximum river discharge reached $2.6 \text{ m}^3/\text{s}$. When examining the substance parameters, different load situations for $\text{NH}_4\text{-N}$ and COD respectively can be discussed. The initial rain does not lead to any CSO activity, but to considerably decreased WWTP emission load with increasing throttle influent. The resulting peak concentration in the receiving water of $2.2 \text{ mg NH}_4\text{-N/l}$ and 103 mg COD/l are by far not tolerable for such a rainfall event. Under such conditions, a continuous WWTP operation is not recommended and should only be run in exceptional cases over a limited period. At a throttle limited to 2 Q_d both stable emission load and an equalisation of the discharge were achieved. The easily recognisable delay of the water peak flow and concentration of $\text{NH}_4\text{-N}$ and CSB are due to the intermediate storage in the sewer system. Thus, for the initial rainfall the best case for the throttle limit upstream of the WWTP would be 2 Q_d . This is different however, with the main rainfall the situation is reversed. Here the operation with 2 Q_d (WWTP inflow) presents the most disadvantageous scenario, as the COD and the ammonium concentration in the river are increased sharply through the stormwater input. The increased conveyance of the stormwater to the WWTP would here have contributed to the reduction of the peak concentrations in the river. This fact is confirmed for all rainfall events with CSO and thus shows the dominance of the CSO activity for the acute river pollution.

Impact of the combined control in the sewer system

For the control of the discharge in the sewer system, the system was provided with regulation devices at the tank throttle. A subordinate combined control which regulates the discharge by its dependence on the water levels in the tank was integrated into the system. The target of the developed control system was to allow for the simultaneous overflow discharge from all three tanks. The water level in all tanks is regulated simultaneously by variation of the throttle aperture. The variation is controlled by integral regulator, defined

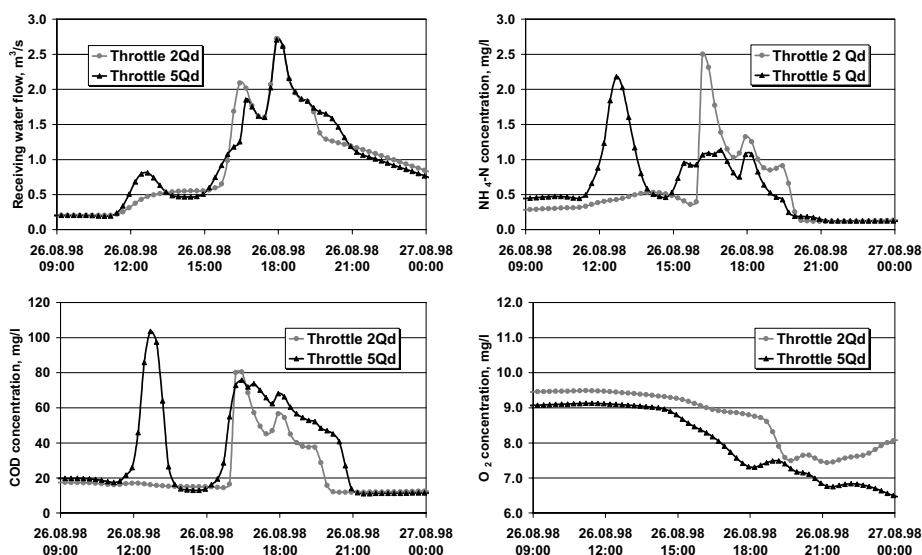


Figure 2 Results of simulation for the river effluent, the $\text{NH}_4\text{-N}$ and COD concentrations at km 0.5, and the O_2 concentration at km 7.5 (26.08.1998)

as directly proportionate to the difference between the respective relative filling level to the achieved average relative filling level. Figure 3 shows the storage volume for one retention tank. Thus cases are compared for a period of 5 days for the current state without control, and two examined control variations, control of two or three tanks, respectively. In case of combined control with only two tanks with the examined tank not being controlled, we recognise only a low volume activation. However, if this tank is subject to the combined control as well, we find a considerably improved utilisation of the storage volume. Yet, the storage volume in this tank cannot be completely exploited because the tank is considerably over-dimensioned and the low corresponding directly drained surface is small.

Through the volume activation in the rain tanks or the inline storage sewer, a reduction of the discharge volume or the discharge load into the receiving water was achieved. For instance, the discharge volume is reduced in case of the control of two tanks by 10.7%, in case of the control of three tanks by 20.7%. The COD discharge load decreased to a similar degree by 9.7% or respectively by 24.8% if three tanks are controlled. Moreover, occurrence of the discharge events is reduced from nine to seven or six events respectively. Thus, volume activation in the existing tanks may diminish the discharge frequency into the receiving water considerably. In contrast to this, hardly any reduction of the maximum discharge concentration of either COD or ammonium can be reached. Here, one has to consider, however, that for the simulation of the pollutants concentration in the sewer system a conservative approach had been used which does not consider sedimentation and biological-chemical processes in the sewer system.

Possibilities for an extended integral handling of drainage systems

The results of the calculations described above already reveal the considerable optimisation potential through the integral approach. Particularly the system-bridging control allows for new perspectives for the operation of the sewer system and WWTP. For this, however, a permanent online control of sewer system and WWTP must be provided. Frequently, extensive online simulations are nowadays additionally used to implement control measurements at the WWTP. Beside the volume activation in the sewer system the throttle outflow into the WWTP can be optimised as well. For this, the inflow discharge to the WWTP is controlled simply in its dependence on the height of the sludge level of the final clarifier. In this case, two drainage components (tanks and WWTP) are controlled interdependently. However, the efficiency of the model-based implementation of such a control strategy crucially depends on the exactness of the process simulation in the final clarifier tank. The issue of how far the calculations are sufficiently exact for a control concept, must still be dealt with in future.

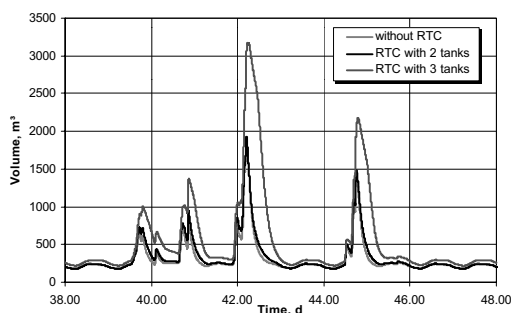


Figure 3 Comparison of storage volume series for a rain retention tank

Applicability and future development of integrated modelling concepts

The classical application area of integrated modelling is the real time control (RTC) of the sewer system. Integrated models will increasingly particularly be used for real time control concepts. Furthermore, today's experiences with WWTP modelling by the ASM concept, as well as the present water quality model with the same conceptual model basis (IWA-RWQM1, Reichert *et al.*, 2001), will boost the attempts towards a sewer system simulation based on a similar concept. For the sewer system, however, there are still considerable deficits, as the physical, chemical and biological processes occurring there are extremely complex. Thus, especially for the issue of pollutant load calculation new impulses for the hydrodynamic pollutant load calculation are needed. In those European countries which have already established an integral handling into their drainage planning, this development has already become very apparent. For instance, in Great Britain and Denmark numerous studies on the origin and fate of dissolved solid pollutants in sewer systems – often referred to “in-sewer processes” – have been run with the goal of improving pollutant load simulation. Currently, attempts are being made in those countries to include the latest findings on the particle transport process and on the biochemical reactions in the sewer system into the legal framework and drainage planning standards in Denmark and Great Britain. Moreover, it can be expected that integrated modelling concepts will increasingly be applied for the compartments “groundwater” and “drinking water”. Currently, first concepts for integration of those major components into an “Integrated Urban Water System” (Rauch *et al.*, 2001) on a unified basis already exists.

Conclusion

Four individual mathematical submodels simulating different subsystems of urban drainage were intercoupled to an integral model and RTC implemented herein. The results reveal that the effect of an RTC control measure may be ambivalent, depending on the load fraction of interest. The drainage system in the catchment investigation could be considerably optimised towards environmental protection and operation efficiency if an appropriate real time control on the integral scale was applied. The main problematic issues are particularly the selection of control strategies and control algorithms in the combined system of sewer system and WWTP, a sufficiently exact tool for modelling the processes in the final clarifier, as well as the variation of the wastewater composition (COD fractionation) during rainy weather. Still, it can be assumed that an ecologically and economically optimised operation of the drainage system will be achieved in the near future through control measures defined on the global scale, e.g. allowing for real time feedback of quantity/quality state within the system. Here, the integral analysis has a massive potential. Furthermore, we expect that integral model-based investigations are suitable for an immission based river evaluation as well. For instance, in Germany the BWK-Instruction Leaflet 3 (BWK, 1999) explicitly emphasises the possibilities of a detailed evaluation, and defines threshold values for the immission parameters in the receiving water for the first time. However, the published definitions concerning the detailed evaluation are rather abstract. Thus, these particular evaluation criteria must be selected and applied very carefully.

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