Storm water management in an urban catchment: effects of source control and real-time management of sewer systems on receiving water quality

T. Frehmann*, I. Nafo*, A. Niemann** and W.F. Geiger*
* Urban Water Management, University of Essen, Universitaetsstr. 15, 45141 Essen, Germany
** Dr. Dahlem Consulting Engineers, Bonsiepen 7, 45136 Essen, Germany

Abstract For the examination of the effects of different storm water management strategies in an urban catchment area on receiving water quality, an integrated simulation of the sewer system, wastewater treatment plant and receiving water is carried out. In the sewer system real-time control measures are implemented. As examples of source control measures the reduction of wastewater and the reduction of the amount of impervious surfaces producing storm water discharges are examined. The surface runoff calculation and the simulation of the sewer system and the WWTP are based on a MATLAB®/SIMULINK® simulation environment. The impact of the measures on the receiving water is simulated using AQUASIM. It can be shown that the examined storm water management measures, especially the source control measures, can reduce the combined sewer overflow volume and the pollutant discharge load considerably. All examined measures also have positive effects on the receiving water quality. Moreover, the reduction of impervious surfaces avoids combined sewer overflow activities, and in consequence prevents pollutants from discharging into the receiving water after small rainfall events. However, the receiving water quality improvement may not be seen as important enough to avoid acute receiving water effects in general.

Keywords Combined sewer overflows; real-time control; receiving water quality modelling; source control

Introduction

Most cities in the densely populated Ruhr area use combined sewers as their drainage system. Some of the acute key impacts on receiving waters associated with combined sewer overflows (CSO) from such urban areas are identified as hydraulic stress, oxygen depletion and ammonia toxicity. In order to reduce the detrimental effects of CSO on receiving water quality, source control and real-time control (RTC) of the sewer system and wastewater treatment plant may be implemented as measures.

Focused urban catchment area

An urban catchment area in the south-east 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 total size of 3.67 km², of which approx. 45.5% is impervious. The settlement structure consists of residential buildings (approximately 15,000 Inh.) with light industry and one large factory. The average annual rainfall amount is approximately 850 mm/a. The catchment area is drained by a combined sewer system including four retention facilities with a total storage volume of approximately 11,000 m³. The dominant facility is an inline storage sewer. The wastewater is treated by a biological wastewater treatment plant (WWTP) with preliminary denitrification. CSOs are discharged into the “Schattbach” creek, a heavily modified water body that will be renaturalised. Accordingly, the simulations are carried out assuming the re-naturalised planning state of the “Schattbach”.

Integrated model of the urban drainage system for the assessment of the efficiency of management strategies

To assess the efficiency of storm water management strategies, and in order to design these strategies optimally, an integrated examination of all the parts of the urban drainage system, the sewer system, the wastewater treatment plant and the receiving water is required (Figure 1). This is necessary in order to investigate and understand the interaction of the overall system.

In this study, four different single models were used: three coupled into one integral parallel model (models for surface runoff, sewer system and WWTP) and one, the water quality model, which ran sequentially. The system component “diffuse loads” was not incorporated into the integrated model. Non-point source pollution is taken into account 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 surface runoff, the model MOSI was developed on the platform MATLAB®/SIMULINK®, using hydrological approaches (Frehmann et al., 2000). The surface runoff is modelled using linear storage cascades. The infiltration losses of natural surfaces is modelled using 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 on the surface. Input data for the simulation are measured rainfall, as well as the daily characteristics for domestic and industrial wastewater production, if available. The conveyance of the discharge and pollutants within the sewer 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 modelling of the water transport is described by the diffusive wave approximation of the St. Venant equation system. This model allows the simulation of an “unlimited” number of substances (dissolved or solid). Approaches for sedimentation, chemical and biological processes in the drainage system can be freely implemented by the user. 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 (Frehmann et al., 2001). The software package SIMBA® (Ifak, 1998) is used to calculate the biological WWTP. By now this software has become a
de-facto standard for dynamic WWTP simulation in Germany. The plant with a preliminary denitrification is simulated based on the model concept ASM 1 (Henze et al., 1987). This individual model was calibrated using measured data and experimental results (Niemann and Orth, 2000). The receiving water was simulated using the software package AQUASIM (Reichert, 1994) with the modelling concept of Niemann (2000).

Water quality modelling approach in the integral model

The selected modelling concept based on a simplified RWQM 1 model (Vanrolleghem et al., 2000). It aims primarily at the evaluation of the acute pollution load through the calculation of the parameters: critical shear stress, oxygen deficits and total ammonia concentrations. The model does not consider individual processes in the catchment in the natural complexity but rather simulates the dominant ones as simplified as possible. The applied model structure was presented in Frehmann et al. (2001). In the calculation, ammonia 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. A distinction must be made 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 (Hvitved-Jacobsen and Harremoës, 1981). Because the simulation of the WWTP treatment performance is based on the ASM concept, the discharged COD is conceptually subdivided into substance fractions. The water quality model distinguishes between easily degradable substances (i.e. dissolved organic substances, Sₛ), slowly degradable substances (i.e. in particulate form, Xₛ) and inert substances (i.e. subject to no degradation, X₁). 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 the WWTP and used for the WWTP simulation). This fractionation was considered to be temporally constant due to the lack of any measured data (Sₛ = 20%; S₁ = 5%; Xₛ = 55%; X₁ = 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 an 80% oxygen saturation. This assumption is tolerable, since the O₂-content in the discharges is largely determined by turbulent flow conditions.

Examined storm water management strategies

Modelling efforts were aimed at the:
• quantification of the efficiency of different RTC measures on sewer overflow reduction,
• determination of acute receiving water effects (critical shear stress, oxygen deficits and total ammonia concentrations) caused by the different RTC measures, and
• assessment of the influence of source control measures and reduction of impervious areas on the different effects caused by the RTC measures.

For this purpose the following scenarios were simulated using the integrated model:
1. Present Situation (PS)
2. Real Time Control (RTC)
3. Reduction of the amount of Impervious Areas (RIA)
4. Reduction of the amount of Impervious Areas and Real Time Control (RIA+RTC)
5. Source Control (SC)
6. Source Control and Real Time Control (SC+RTC)
The first scenario (PS) represents the present situation without source control and RTC measures. In the second scenario (RTC) the total storage volume in the sewer compartment serves the system optimisation. For this reason the water levels in all overflow structures are optimised. Flow towards the wastewater treatment plant is kept constant, which means that RTC measures are only taken for the sewer compartment. In the third scenario (RIA) the amount of impervious surfaces producing storm water discharges were reduced by 10%. These areas were found by the GIS-Application to be suitable accordingly to defined criteria 1. Impervious surfaces to be disconnected are roofs or “clean” private surfaces 2. There must be enough pervious surface available for the infiltration of storm water from disconnected surfaces; ratio of available pervious surface/impervious surface to be disconnected from sewer > 1. 3. The soil of the existing pervious area for the infiltration has a hydraulic conductivity between $10^{-3}$ and $10^{-6}$ m/sec, and the groundwater level below the topsoil is at least 1.5 m. 4. Instead of the points 2. and 3. there is a receiving water in the vicinity of the surfaces to be disconnected. RTC measures were not used in the third scenario but implemented in the fourth scenario (RIA+RTC). In the fifth scenario (SC) the resulting dry weather flow through reduction of fresh water consumption was taken into account. The fresh water consumption has been considerably reduced in Germany in the last 20 years through consumer behaviour and the usage of water saving devices. For example, these measures led to a water consumption decrease from 145 l per person and day in 1990 to 128 l per person and day in 2000 (Statistics from Bundesverband der deutschen Gas- und Wasserwirtschaft e.V., 2001). A water consumption of 130 l per person and day instead of 180 l per person and day was assumed in this paper. In the sixth scenario (SC+RTC) RTC measures were considered in addition to the source control solution in the fifth scenario.

**Efficiency and impact assessment of the examined storm water management strategies**

The comparison of the effects of the different management measures was carried out for a summer period from 15 July 1998 to 16 September 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. 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.

For the integrated approach, first the individual models were calibrated and verified. The calculation of the surface runoff, the transport in the sewer system, and the treatment in the WWTP ran in 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 individual systems are operated completely separate from each other. At the outflow of the last inline storage sewer before the WWTP there is a stand-alone gate controlled by an MID.

The various management measures are evaluated:

- by comparing the different solutions taken to the present situation regarding the outflow volume from the sewer system to the WWTP, the discharge volume and the COD and NH$_4$-N load to the receiving water,
- by comparing the emission parameters from the sewer system and WWTP 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 ($\tau_{\text{crit}} = 10 \text{ N/m}^2$), ammonia toxicity (0.1 mg NH$_3$/l) and oxygen deficit (4 mg O$_2$/l).

**Impact of the management measures on CSO volume and load**

Through RTC 3% more wastewater volume is conveyed to the WWTP in comparison to PS (Figure 2). It is therefore legitimate to ask whether RTC implementation is reasonable in regard to the cost of such a measure. Beside that it has to be considered that RTC also leads to a reduction of CSO volume by 12% and to a discharge load decrease of 3% regarding COD and 5% regarding NH$_4$-N in comparison to PS. As expected, the maximum CSO volume reduction through a single measure in the simulation period could be achieved with RIA by approximately 32% in comparison to PS. At the same time the COD and NH$_4$-N discharge loads are also reduced in this scenario by respectively 14% and 15% in comparison to the present situation. This is due to the fact that the total number of CSO activities is reduced using RIA. The implementation of RTC additionally to RIA leads to greater reduction of the CSO volume and the COD and NH$_4$-N discharge loads by respectively 8%, 3% and 5% in comparison to RIA as a single measure. Through the reduction of fresh water consumption (SC) the outflow volume from the sewer to the WWTP decreases by up to 15% in comparison to the present situation. But this measure leads only to a discharge volume reduction of 4%. Source control measures may therefore be recommended when the existing WWTP is overloaded. Regarding CSO quality aspects, SC as a single measure leads to the maximum reduction of COD and NH$_4$-N discharge loads by respectively 18% and 26% in comparison to PS. In spite of the implementation of RTC additionally to SC there is less CSO volume reduction in the sixth scenario as in the third one. But through the combination of SC and RTC the COD and NH$_4$-N loads in the CSO could be reduced by respectively 22% and 31% in comparison to the present situation. However, RIA and SC can be identified as the most efficient measures to reduce CSO volume (RIA) and discharge load (SC). Considering the cost and the difficulties encountered in densely populated areas for reducing the amount of impervious surfaces draining to the combined sewers, SC may be seen as a simple but very important measure for the discharge load management.

**Impact of the management measures on the receiving water**

It can be shown as a result of the sewer system simulation that the examined measures, especially the reduction of impervious surfaces draining to sewers and the reduction of fresh water consumption, diminish the combined sewer overflow volume and load considerably. But are these good results for the sewer system also leading to water quality improvement in the receiving water or are they even contra-productive from an emission point of view?

![Figure 2](https://iwaponline.com/wst/article-pdf/46/6-7/19/42479/19.pdf)
For the impact assessment of the examined management measures on the receiving water two different types of rainfall events have to be distinguished: small rainfall events with resulting receiving water flow lower than 1.1 m³/sec and heavy rainfall events leading to receiving water flow greater than 1.1 m³/s. For small rainfall events all the examined measures have a slightly positive effect on receiving water flow and quality (Figure 3). Especially with RIA, such rainfall events didn’t lead to any CSO activity, and in consequence to any hydraulic stress and pollutant discharge in the receiving water. The other measures reduce the peak concentrations of COD and NH₄-N and the duration of the concentration effect in the receiving water in comparison to PS. Also during a heavy rainfall event, the examined management measures lead to a slight river water quality improvement (Figure 4). Only with RTC is the receiving water peak flow higher than in the present situation. But RTC leads especially to a diminished concentration effect duration, in addition to the reduction of the peak concentration regarding COD and NH₄-N in comparison to PS. The effects of the combined measures RIA+RTC and SC+RTC on the receiving water are respectively the same as the combination of the effects of the single measures RIA or SC with RTC. This means that the resulting receiving water flow peak or the pollutant concentration peak is likely to be the same by implementation of the combined measures as in the single measures RIA or SC; the pollutant concentration effect duration is the same as by the implementation of RTC alone. However, for both types of rainfall events, the critical limit values for the immission parameters ammonia toxicity and oxygen deficit were not exceeded at any time within the simulation period. Only the critical bottom shear stress in the receiving water was exceeded once in PS as well as in all examined management measures, due to the heaviest rainfall event in the investigation period with a rainfall depth of 13.9 mm. Moreover, the resulting positive receiving water effects of the examined measures in comparison to PS are not important enough from an immission point of view. These measures reduce the discharge load from sewer systems, but may not be used with the goal to reduce the acute critical receiving water impact of CSO. Only RIA may be seen as an efficient measure to avoid CSO activity after small rainfall events. When a CSO activity occurs, RIA can reduce the peak flow and the peak concentration of COD and NH₄-N in the receiving water in comparison to PS considerably.

Figure 3 Results of the water quality simulation – typical effects of the management measures on receiving water after a small rainfall event
Conclusion

All of the examined measures reduce the CSO volume and the CSO discharge load into the receiving water. However, only the source control measures and the reduction of impervious surfaces in the catchment area are efficient measures for urban storm water management. The results of the investigation within the chosen urban catchment area, which has a steep sewer system, show that the implementation of real-time control measures does not lead to any significant improvement regarding the CSO activity and the receiving water quality in comparison to the present situation. Even if the source control measures and the reduction of impervious surfaces diminish the pollutant discharge loads from the sewer system considerably, the positive effects of these measures in the receiving water are not suitable for avoiding detrimental acute receiving water effects in general.

References


