The influence of stormwater treatment on the hydraulic and pollution load – balance for an entire river basin

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Abstract The installation of about 500 stormwater detention facilities (SDFs) led to a significant drop of the pollution originating from stormwater runoff in the river basin of the Ruhr which covers 4,488 km^2. The German technical directives on the design of SDFs are briefly outlined and the specific costs for such plants are given. The average costs for one kilogram COD held back by SDFs in combined systems amount to € 3.73 (calculated without consideration of the subsequent removal in the municipal wastewater treatment plant (WWTP)). The tank volume for stormwater storage can be minimised by application of real-time management systems which allow a dynamic operation of all SDFs in a catchment area.

Keywords Costs; German requirements; hydraulic load, pollution load; stormwater

Introduction

The Ruhrverband (Ruhr River association) is responsible for the management of the entire catchment area of the Ruhr river which is 220 km long. It is one of its major goals to minimise the pollution load of the river which serves more than 5 million people with drinking water. To satisfy the complex needs of all members (58 municipalities, about 700 industrial and about 150 other water-consuming companies including drinking water-works), the Ruhrverband operates 8 reservoirs and 92 WWTPs. About 20 years ago, it became evident that to improve the situation – in many cases – it would be less expensive to invest in additional stormwater treatment than to further upgrade the WWTPs. Most member towns of the association have combined sewer systems. With an average rainfall in the catchment area of about 1,050 mm/a, Ruhrverband currently operates about 500 SDFs the only purpose of which is to hold back and store the combined wastewater accumulating when it rains so that it can be transferred to the sewage treatment plant, after the rainfall event.

The overall catchment area of the Ruhr covers 4,488 km^2 and 5.7% of this area is "sealed up" ground. Figure 1 shows the distribution of the different COD-sources for the entire river basin. Most figures are measured values, the assessed ones – based on long-term experience and literature – can be judged equally reliable. The annual COD-load at the river mouth comes to 30,000 tons. With an overall amount of 40,000 tons of COD entering the river every year, the actual removal by self-purification is assumed to be in the range of 10,000 tons/a. The COD-discharge from WWTP effluents amounts to 13,000 tons, whereby 11,500 tons stem from conventional sewage treatment and 1,500 tons from stored and subsequently treated stormwater. An overflow of 5,000 tons/a from the SDFs cannot be avoided. Some 1,000 tons originate from separate sewage systems. But by far the largest quantity has its origin in non-point sources from the unsealed area (21,000 tons). In absolute terms, all figures appear to be rather small if compared with the overall load contained in the raw sewage which is in the range of 130,000 tons of COD per year. All arrow-shaped bars on Figure 1 have been sized true to scale with the exception of that for the municipal sewage load, representing the bulk of these 130,000 tons, which would
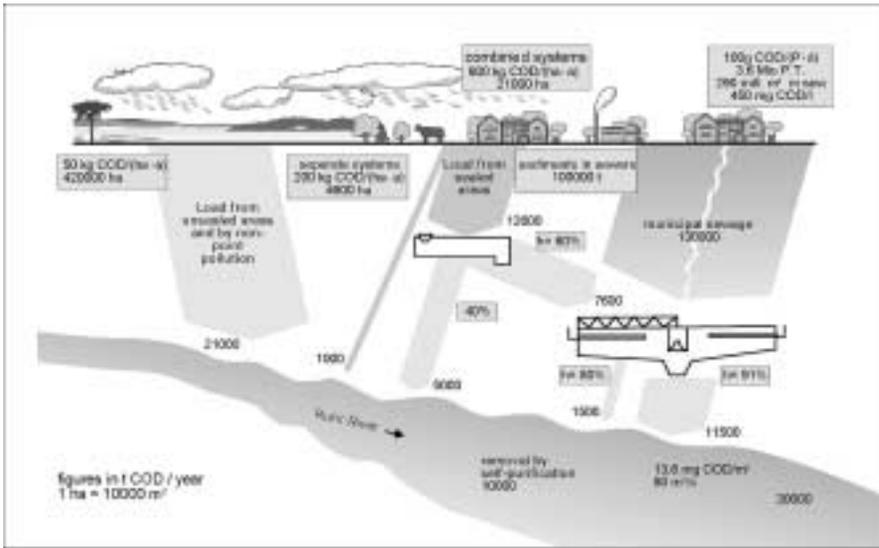
Figure 1 Distribution of different COD-sources for the entire river basin of the Ruhr (4,488 km^2)

otherwise have spoilt the graph. To enhance the efficiency of stormwater treatment it is important not to neglect the effect of sedimentation inside the sewerage systems. The COD-load accumulating in the sediments (estimated to be 100,000 tons) should be minimised by appropriate operational measures to prevent remobilization and discharge into the receiving waters during stormwater runoff.

Developments in stormwater treatment in Germany

In the Federal Republic of Germany, stormwater overflows were the typical structural features used for storm runoff in combined sewer systems up to the mid-1970s. Runoff distribution was their only task: a defined portion of the combined water flow in the sewerage system was taken to the WWTP and any excess amount released. Up to the early 1960s, sewage dilution was the method of choice used to dimension the combined sewer overflows (CSO). It meant that during rainfall the combined wastewater was discharged early into the receiving waters, as the threshold to be passed was relatively low. Normally this happened when sewage dilution was greater than eight times (one part wastewater to seven parts stormwater).

A first improvement of the unsatisfactory situation was achieved in 1962 with the introduction of the "Vorläufige Richtlinien für die Bemessung und Gestaltung von Regenüberläufen" (provisional guidelines for the dimensioning and design of stormwater overflows). This major directive was based on the determination and definition of the critical amount of rainfall (dimension: l/(s ha)) that would always have to be transferred to the WWTP. Only if that limit value was exceeded, could combined water be discharged via stormwater overflow. However, in the early 1970s, which saw a boom in building activities, it soon became evident how much the high load of pollution still occurring, in particular, at the beginning of a rainfall event affected the status of the waterbodies.

To tackle this problem, systematic and intensive research and development efforts were undertaken, which lasted several years, to determine and better understand the relevant transport processes of pollutants within the sewerage systems and the runoff conditions during rainfalls (Krauth, 1971; Geiger, 1984). The investigations showed, among other things, that the assumption of a rather homogeneously distributed contamination during stormwater runoff and of a stratificational structure of contaminants in the sewer systems

was no longer tenable. Significant differences were found in the degree of stormwater pollution, which were essentially a function of

- the structure of the sewerage system,
- the size of the catchment area,
- settling behaviour,
- the resuspension capacity.

Based on the findings from these studies, so-called "Regenüberlaufbecken" (stormwater detention facilities (SDF)) were developed. It is their task to significantly reduce both the amount of discharged overflow as well as of the maximum flow rate being directed to the treatment plant (compared to stormwater overflows), by storing the highly concentrated combined water and sending it to the WWTP later, after the rainfall. These measures help to take about 65% of the hydraulic stormwater runoff and about 85% of the combined sewage load accumulating during stormwater runoff to a WWTP for treatment. Since 1977, such SDF structures have become standard components in all combined sewage networks in Germany. Their design is subject to regulation in compliance with a specific directive (ATV, 1992). In Germany, there are currently more than 15,000 stormwater detention facilities in service.

Several variants of stormwater detention basins have meanwhile been developed taking into account the above described relationship of stormwater pollution to specific parameters and, in particular, to local conditions. The detention basins may be designed either as collecting tanks (Fangbecken FB) or as continuous flow tanks (Durchlaufbecken DB). Integration within the existing drainage network may be established in the form of main or side sewers. As regards the configuration, there are several alternatives: rectangular or circular basins (covered or open) or storage sewers with **d**esigned **i**nline **s**torage **c**apacity (DISC-sewer).

It is the major objective of stormwater treatment to take the largest possible amount of pollutants to the WWTP. Basins operated as side sewers were found to support this goal more effectively than main sewers, which, determined by the system, continue to receive wastewater for quite a while after a rainfall event. And if these sewers have not been fully emptied before another discharge of combined water takes place, the pollutant concentration in the effluent released in the receiving waters will be higher. As pollutants will settle during every filling of the SDFs, the basins must be carefully cleaned when they are empty. Under favourable conditions, this is achieved by self-cleaning with the help of the dry weather flow, in particular, in storage sewers and circular basins operated as main sewers. The other basin types are generally equipped with automatic cleaning devices. To minimise the input of pollutants into the stormwater detention basins, hydrodynamic separators being placed prior to the basin have proved to be suitable for the purpose of holding back as many contaminants as possible in the drain network.

Investment costs for stormwater treatment

The Ruhrverband has compiled and analysed through several years all data from the design and construction of about 160 SDFs to check the investments made in the field of stormwater treatment. The facilities were classified as follows:

a) prefabricated tank, designed as open or covered system
b) tank, designed as conventional-type open basin
c) tank, designed as conventional-type covered basin
d) sewer with **d**esigned **i**nline **s**torage **c**apacity (DISC-sewer), built under normal boundary conditions (location within green areas or secondary traffic areas, open construction)
e) DISC-sewer, built under more difficult boundary conditions (location within primary

traffic areas, tunneling construction, extremely low groundwater level, rocky building ground, or more intensive ground water management)

The investment costs for the different construction measures include both the structural components, with specific overflow structures and throttle devices, and the machinery and instrumentation required. The engineering fees have also been considered. However, not included are the construction expenses for the overflow sewers and discharge structures, as these are particularly subject to local conditions, as for example, the distance to the receiving water or difficulties encountered in construction. The specific building costs are expressed in € per cubic metre of storage volume (see Table 1) and average 1,000 € /m^3 for all 160 detention tanks. In Figure 2, the relationship between investment cost and basin size is indicated for the different construction types. Facilities with a low storage volume were found to be relatively expensive due to the required basin overflow and throttle structures and the necessary machinery and instrumentation.

In combined sewerage systems, stormwater treatment is synonymous with the co-treatment of the pollution load held back in the downstream WWTP. The required hydraulic peak capacity of the WWTP decreases as a function of the available storage capacity in the sewage system. Because of this, the question whether or up to what point it would be better to improve the treatment capacity of a WWTP rather than to invest in the construction of new SDFs in order to meet specified pollution limits, should not be neglected. Against this background it was investigated, by example of one specific catchment area, which changes in volume would be involved for the stormwater basins, sludge activation tanks and secondary clarifiers, if the combined water inflow rates were 1.5 to 3.5 times higher than the dry weather flow (DWF). The results, given in Figure 3, show that the total volume first

Table 1 Amount, total volume and specific costs for the construction of the investigated different types of SDFs (cost level of 1996) (Willems *et al.*, 1999)

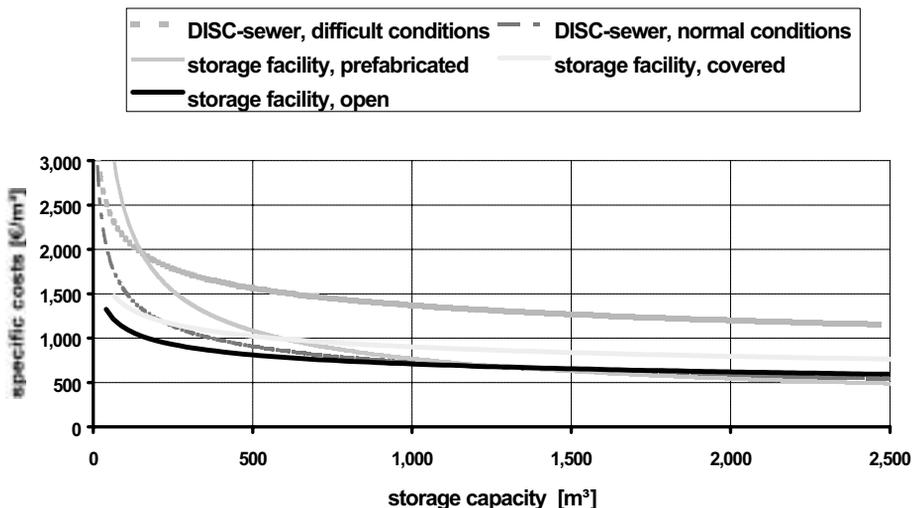| | Stormwater storage tank | | | DISC-sewer | |
	prefabricated structure	open in situ structure	covered in situ structure	normal conditions	difficult conditions
amount	12	21	25	59	40
total volume	8,608 m^3	33,751 m^3	24,153 m^3	45,416 m^3	29,175 m^3
specific costs	917 €/m^3	686€/m^3	1,004 €/m^3	815 €/m^3	1,526 €/m^3

Figure 2 Specific costs for the construction of SDFs as a function of storage capacity
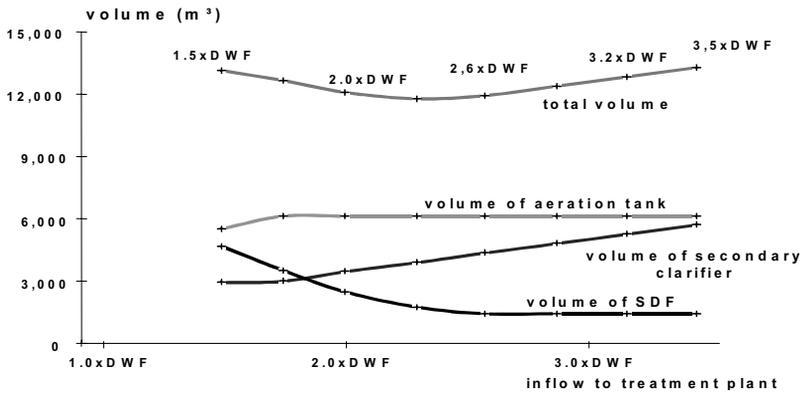
Figure 3 Volumes of detention basin, secondary clarifier, aeration tank and total volume versus inflow during wet weather conditions

declines with growing combined water runoff, with its lowest point at a rate 2.3 times as high as the DWF, but then goes up again as the volume in the secondary clarifier continues to rise, whereas the volume of the SDF remains at a minimum level (Bode *et al.*, 1995).

Specific costs of pollutant retention by stormwater treatment

As of December 31, 1999, the Ruhrverband operated 478 SDFs with a total volume of around 410,000 m^3. The above mentioned cost analysis showed investment costs of about 1,000 €/m^3. Considering the fact that many detention basins were already built some years earlier, the cost estimation was based on a mean value of 500 €/m^3, which gives an amount of total investment of approx. € 205 million. Assuming that the annual expenditure for depreciation, interest costs and maintenance is in the range of 10% of the overall capital investment, a sum total of € 20.5 million per year is obtained.

Beside the costs for investments, also those for the operation of the facilities must be considered. According to a cost analysis undertaken by the Ruhrverband, plant attendance takes about 110 hours per plant and year. With a cost-effective hourly rate of € 26, the pure personnel expenses amount to about € 2,900 per plant and year. To be added are further costs (for materials etc.), so that the overall operating costs amount to about € 3,200 per plant per year. And the required total costs for all 478 SDFs on stream come out to around € 1.5 million/a.

Thus, the overall annual costs for building and operating stormwater treatment tanks add up to around € 22 million. If this amount is related to the effectiveness of such facilities, as described in the introduction, with regard to the retention of 5,900 (= 7,600–1,500) tons of COD/a, the specific costs work out at around € 3.73 per kg COD retained. Still to be added is the cost for COD-removal in the WWTP which averages approx. € 1.00 per kg COD.

Though the retention costs of 3.73 €/kg COD may appear rather high compared with the removal costs of 1.00 €/kg, the interim storage of combined sewage and subsequent treatment can be regarded as the most economical route for enhanced water pollution control. This is particularly the case where a level of wastewater purification as high as that in the catchment area of the Ruhr river has already been achieved. On the other hand, any approach to outperform the purification results so far achieved by the treatment plants would definitely cost more than € 4.73 per kg COD, because it would involve the application of more methods like, for example, filtration and the use of activated carbon or membrane technology.

Operational support by central visual display and application of real time control

It is known that stormwater storage normally takes place at sites far away from "manned" facilities. To optimise plant performance it is vital to collect real-time information on the actual operating status of the facilities and to transmit them to a central control station (preferably in the WWTP that serves the catchment area onwhich the basins are located). Meanwhile, the Ruhrverband has equipped many WWTPs with central visualisation systems. These allow the labour demand to be updated so as to better respond to the actual requirements. Figure 4 gives an example of such a general chart for seven SDFs.

The different bars show the status of volumetric flow and level in the SDFs in relation to the S value (S – for the specific situation), which is stored as reference value by the automatic controller *in situ*, and the actual value (I) are indicated. The end of the scale stands for 100% (of flow and volume). In the line below the different bars, this example also indicates the position of the regulating unit (for instance, slide gate open/closed, motor failure, slide gate failure, and so on). The letter "M" on the chart stands for motor trouble in facility V. The capital "S" in the middle of the chart indicates that there is an operating disturbance in the overall system (in this case the mentioned "M").

The primary task of stormwater treatment is to minimise the pollutant load discharged into the river by combined sewer overflow (CSO). The desired result is not achieved on a short-time basis, which means, in the course of any single overflow event, but as an average mean over a period of many years. Specific interventions in the discharge and detention processes, made possible by real-time control, lead to an improved use of the overall available detention capacity in a sewerage system. For one thing, this results in a lower discharge rate of hydraulic load and, for another, in a higher treatment rate in the WWTPs due to the additional pollution load arriving there.

The Ruhrverband has already been practising real-time control for some years in the Ense-Bremen WWTP (Weyand, 1993, 1996). The effort is geared to achieving a uniform level during a rainfall event in all seven SDFs being operated in the catchment area. This is achieved by continuously adapting the different basin outflow discharges to the actual load status of the specific structure and that of the overall catchment area. In view of the fact that problems with monitoring and control devices can hardly be avoided in day-to-day operation, it was decided to implement just a simple, easily understandable control strategy which significantly contributed to minimising failures in the control system due to malfunction of gauges. Evaluation of the drainage scenario documented over a period of many years provided evidence for the success of this specific real-time control measure. Table 2
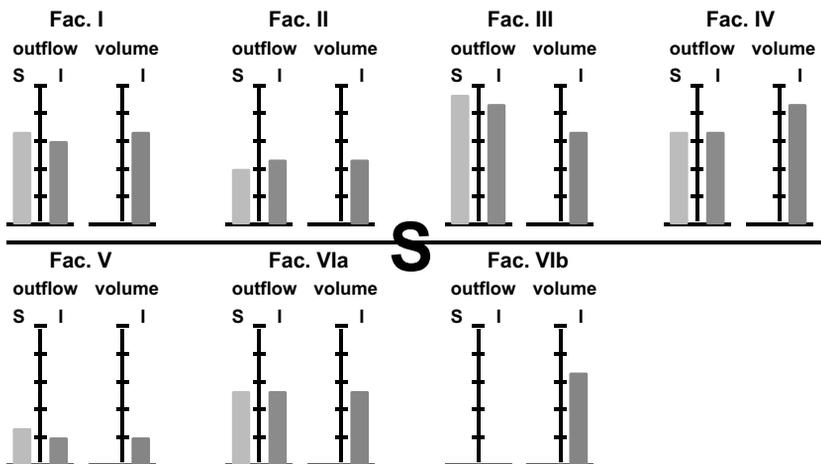

Figure 4 General chart with real-time information on outflow and level of seven SDFs

Table 2 Parameters of the Ense-Bremen drainage system for controlled and uncontrolled operation

	Operating condition		
	without control	with control	
		normal storage capacity	reduced storage capacity
Specific storage volume [m³/ha]	31.5	31.5	25
Amount of CSO events per year	16	14	16
CSO discharge in ratio to the total runoff per year	0.28	0.21	0.27
Mean use of storage capacity in ratio to the available overall capacity	0.70	0.71	0.76

summarises the results by comparing different parameters in a system with and another without control.

Application of real-time control means the possibility to reduce, for one thing, payroll costs for control and inspection due to optimised operational conditions and, for another, investment costs. Assuming, for example, that both alternatives – controlled and uncontrolled systems – are equally efficient with regard to water quality, it is safe to say that 20% of the otherwise necessary storage volume can be saved by the use of real-time control. This is illustrated by the figures given in the last column of Table 2. However, this saving possibility compares with the additional expenditure for the design and implementation of the new control strategy, the installation of non-switched connections between field and central control stations, and for the operational staff.

Conclusions

The most noticeable fact about stormwater detention facilities is that they contribute significantly to the protection of waterbodies. For the catchment area of the Ruhr river this means that an additional amount of about 7,600 tons of COD is taken to downstream WWTPs for removal, which prevents some 5,900 tons of COD from entering the receiving waters. Stormwater treatment helps reduce COD loads being yearly discharged by one fourth, from 24,100 t/a to 18,000 t/a. For small recipients the beneficial effect is even much higher since their aquatic life suffers to a great extent from brief overflow spills (containing big loads). However, if this positive pollution load balance is to be upheld or even enhanced, it is necessary to carefully monitor all operations so that any finding with regard to the structural design and operational attendance of such facilities can be integrated in the continued optimisation process. And only in this way will it be possible to keep the specific costs for the retention of pollutants at a level acceptable for all parties concerned.

Against this background, SDFs have meanwhile proved to be indispensable components in sewerage systems. However, the great number of already existing facilities, still bound to rise in future, also means a steadily increasing expenditure for operational attendance and monitoring. The required investment for a medium-sized SDF, with a capacity of around 900m³ and specific costs of around € 500 per m³, comes to € 450,000.

The use of state-of-the-art instrumentation and control technique is necessary to meet the current stringent requirements for the protection of waterbodies. And central monitoring and control of all major SDFs within a specific catchment area is the suitable tool to "customise" jobs and thereby optimise manpower planning. Central evaluation of the retention and discharge behaviour in the different facilities also allows a better assessment of the actual efficiency of the specific plants and its adjustment to the prevailing load conditions by application of real-time control systems.

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