A new database on urban runoff pollution: comparison of separate and combined sewer systems

H. Brombach*, G. Weiss* and S. Fuchs**

* Umwelt- und Fluid-Technik Dr. H. Brombach GmbH, Steinstrasse 7, 97980 Bad Mergentheim, Germany (E-mail: *uft@uft-brombach.de*)

** Institut fuer Siedlungswasserwirtschaft, Universitaet Karlsruhe (TH), Adenauerring 20, 76128 Karlsruhe, Germany (E-mail: *stephan.fuchs@isww.uka.de*)

Abstract For a long time people have questioned what the "best" sewer system is for limiting the pollution load released into the receiving waters. In this paper the traditional separate and combined sewer systems are compared using a pollution load balance. The investigation is based on measured concentration data for a range of pollutant parameters in the sewer from the new database "ATV-DVWK Datenpool 2001". The approach also accounted for the wastewater treatment plant outflow which contributes to the total pollutant load considerably. In spite of a number of neglected effects, the results show that the separate system is superior to the combined for some parameters only, such as nutrients, whereas for other parameters, e.g. heavy metals and COD, the combined system yields less total loads. Any uncritical preference of the separate system as a particularly advantageous solution is thus questionable. Individual investigations case by case are recommended.

Keywords Combined sewer system; database; measured concentrations; separate sewer system; urban runoff pollution

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Introduction

What is the "best" sewer system to minimize pollution of the receiving waters at a minimum cost? This question has been discussed since the beginning of urban drainage. Two traditional solutions were developed early on, the combined and the separate sewer system, see Figure 1. These systems still form the majority of modern sewer systems all over the world. Together with improved wastewater treatment at the end of the pipe, river quality has considerably improved in industrialized countries in the last third of the 20th century. In the past years, several modified drainage systems have been developed in order to keep low-polluted water out of the sewers by best management practices (BMPs) like on-site infiltration, source control, etc. Generally, however, there is a strong world-wide trend towards the separate system, at least in industrial nations. For example, in the United States the Clean Water Act of 1972 (*cf.* WEF, 1997) recommends separate systems. Combined systems are regarded as to cause high pollution and also hygienic risks.

Of the German population of nearly 82 million inhabitants, around 2/3 are served by classical combined sewer systems. In the past years, nearly 24,000 combined sewer overflow (CSO) tanks have been built. Like in other countries, a renaissance of the separate system can be observed. Regardless of the higher construction and maintenance costs of two systems versus one system, it is even recommended as standard solution in some German federal countries. In separate systems, however, there are far fewer tanks for stormwater treatment, only around 2,000 (Brombach, 2002), pure retention basins not included. Runoff in the storm sewers of separate systems is reputed as to be rather clean so that there is no urgent need to treat it before releasing into a river – in spite of recent publications such as ATV-DVWK M

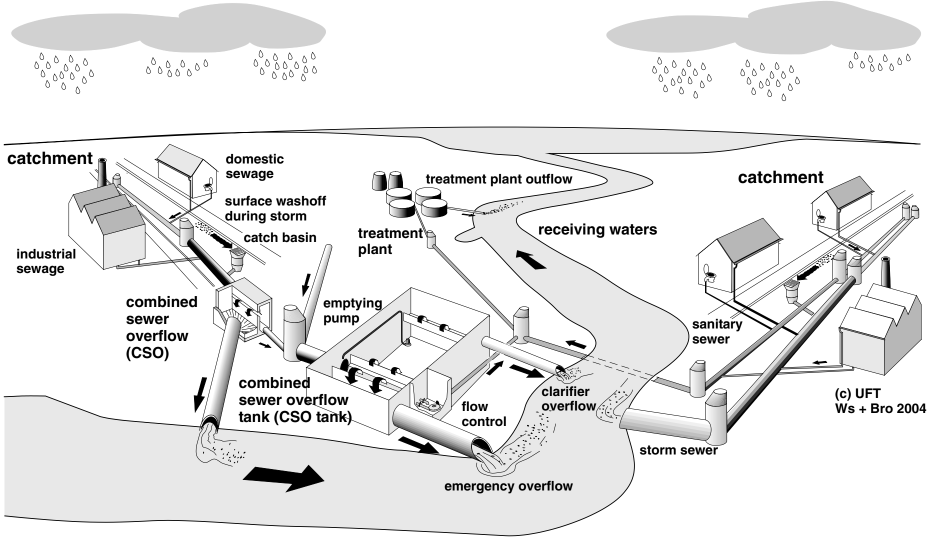

Figure 1 Traditional combined (left) and separate (right) sewer systems

153 (2000). This new standard requires stormwater treatment, dependent on the pollutant potential of the drainage basin land use and on the sensitivity of the receiving waters.

In a new collection of world-wide measured urban runoff pollution data, pollutant concentrations from separate as well as from combined sewage systems have been compiled into a comprehensive database "ATV-DVWK Datenpool 2001", sponsored by the German Association for Water, Wastewater and Waste (ATV-DVWK). Details are shown by Brombach and Fuchs (2003), see also Fuchs *et al*. (2004). The present paper tries to apply some data from the new database in order to compare the performance of different sewer systems.

Methods

The classic separate and combined sewer system – the latter including CSO tankage – are compared, considering a typical urban drainage basin. It is a straightforward, yet very simple approach to estimate some long-term averaged annual flow volumes. For a pollutant balance, the mean pollution loads for both sewer systems can be obtained by multiplication of the flow volume times the mean concentrations taken from the database. More advanced dynamic approaches such as long-term quantity-quality simulation would not reveal more exact results because of uncertain model assumptions. Our approach is based on measured concentrations only.

Annual flow volumes

The idealized simplified systems under comparison are shown in Figures 2 and 3. The comparison does not assume any treatment of storm runoff in separate systems. Runoff, which is bypassing the sewer and going directly into the river via groundwater or overland flow, is neglected here. On the other hand, infiltration/inflow (I/I) is added, also called parasite water, since it is a decisive property for balancing the flow volumes. Furthermore, modifications of the sewer systems such as infiltration of low-polluted storm

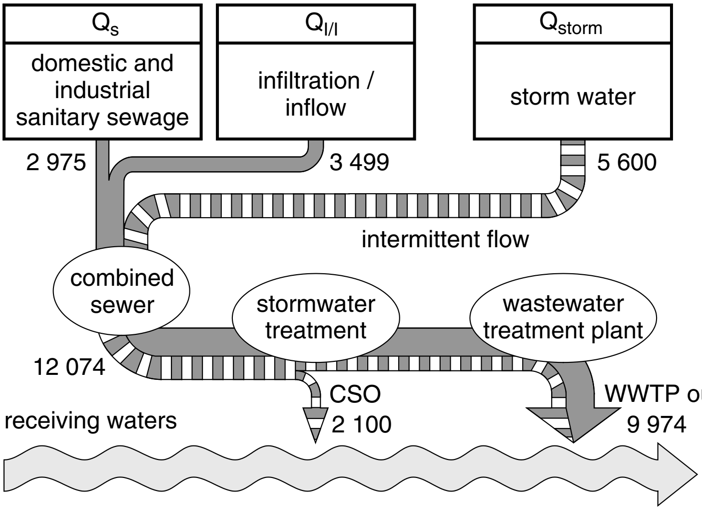

Figure 2 Idealised combined sewer system with average flow rates in $m^3/(ha_{imp} \cdot a)$ according to Table 1

water into the soil are not considered. All flows are assumed to reach finally the receiving waters.

Average annual water volumes in German urban sewerage systems and the ratio of average flow volumes are taken from Weiss *et al*. (2002), based on a long-term evaluation of 34 real sewage systems in South Germany including the treatment plant. The approximate runoff volumes of the flow components of Figures 2 and 3 are computed in Table 1, using these average values. For some missing parameters, values typical for German sewer systems were chosen. All volumes are related to one hectare of impervious surface, which is indicated by the unit "ha_{imp}".

A combined system is assumed to feature some 25 to 35 m^3/ha of CSO storage capacity, which is typically for modern German combined systems. This system will usually release around 30 to 50% of the annual storm runoff as non-treated combined sewage directly into

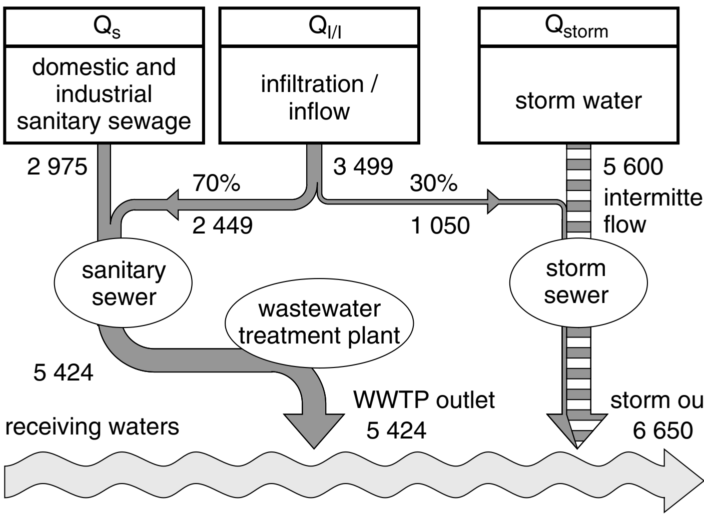

Figure 3 Idealized separate sewer system with average flow rates in $m^3/(ha_{imp} \cdot a)$ according to Table 1

Table 1 Typical German average annual runoff volumes per hectare of impervious area

General catchment data: domestic and industrial sanitary sewage		**Combined sewer system: combined sewer**	
population density	62.7 inh./ha_{imp}	sewage volume	12,074 $m^3/(ha_{imp} \cdot a)$
water consumption	130 l/(inh. · d)	**stormwater treatment**	
sewage volume	2,975 $m^3/(ha_{imp} \cdot a)$	rate of storm runoff spilled at CSOs	37.5 %
infiltration/inflow		*combined sewage, released to river*	*2,100 $m^3/(ha_{imp} \cdot a)$*
percentage of sewage flow	118%	**wastewater treatment plant**	
I/I volume	3,499 $m^3/(ha_{imp} \cdot a)$	*treated sewage, released to river*	*9,974 $m^3/(ha_{imp} \cdot a)$*
percentage of I/I flow in the sanitary sewer of the separate system	70%	**Separate sewer system: sanitary sewer**	
storm water		sewage volume	5,424 $m^3/(ha_{imp} \cdot a)$
annual rainfall	800 mm/a	**storm sewer**	
rainfall forming runoff	70%	*stormwater, released to river*	*6,650 $m^3/(ha_{imp} \cdot a)$*
effective rainfall	560 mm/a	**wastewater treatment plant**	
storm runoff volume	5,600 $m^3/(ha_u \cdot a)$	*treated sewage, released to river*	*5,424 $m^3/(ha_{imp} \cdot a)$*

the river via the overflow structures. In Table 1, a rate of 37.5% is assumed to keep compatibility to Weiss *et al.* (2002).

For the separate system, the same basic flow volumes are assumed. The total I/I volume is also assumed as equal in both systems. A combined sewer will drain all I/I, in a separate sewer system, it is assumed that 70% of the parasite waters are entering the sanitary sewer and the storm sewer drains the remaining 30%. This is a reasonable split since most German houses have basement drainage, and the sanitary sewer is laid at a deeper level than the storm sewer.

Pollution load balance

The next step towards a balance of the pollutant loads of both drainage systems is to assume mean pollutant concentrations. A recent investigation has compiled worldwide measured pollution concentrations in different components of the urban water cycle, see Brombach *et al.* (2003) and Fuchs *et al.* (2004). In particular, the investigated flow components of the combined system were dry weather flow, wet weather flow (combined sewage), and overflow from CSO structures. Of the separate system, storm runoff in the storm sewer was investigated. The data was collected for a period of 33 years, from 1968 to 2001. Data on a total of 34 parameters were collected and added to the new database "ATV-DVWK-Datenpool 2001," which contains 425 records. Some of these records with more than 350 single sample values. This includes the well-known NURP study from the United States (USEPA, 1983), as well as more recent European research work, see Table 2 and Figure 4. This database represents today's knowledge on measured pollutant concentrations and allows for statistical analysis. The data is freely accessible over the Internet.

Moreover, statistical analysis was carried out for 20 selected parameters. Figure 5 shows an example. In the present investigation only 15 pollution parameters were used, such as shown in Table 3. The parameters represent different classes of pollutants.

The distribution curves like Figure 5 yield detailed statistical information such as the upper and lower quartiles. In the present investigation only a single "typical" or "average" concentrationwas sought for any of the 15 parameters in the investigated components of flow.

Table 2 Confrontation of the number of evaluated records in five comparable studies

Study	NURP USEPA (1993)	Brombach	Lange & Moog	Duncan	Brombach and Fuchs (2003)
		(referenced in Brombach and Fuchs 2003)			
Period	before 1978	before 1993	before 1995	before 1999	1968–2001
Separate sewer system	81	21	12	473	209
Combined sewer system	0	29	0	0	216
Sum	**81**	**50**	**12**	**473**	**425**

The pollution balance has been based on the median values (50 percentiles) rather than the arithmetic mean: Since the histogram of most concentrations is left-skewed, the arithmetic mean would overestimate the "typical" overflow concentrations.

To consider the effect of the wastewater treatment plant (WWTP) whose outflow shows a small yet definite remaining pollution, Table 3 shows also typical mean outflow concentrations of German state-of-the-art biological treatment plants including nutrient elimination which were taken from ATV-DVWK (2003), NRW (2000) and UBA (2002). For the present first approach, it was not possible to distinguish between WWTPs that serve combined or separate sewer systems. For TSS, a typical outflow concentration of 7.5 mg/l was assumed (not investigated in the references mentioned). For SS, a WWTP outflow concentration of near zero is expectable.

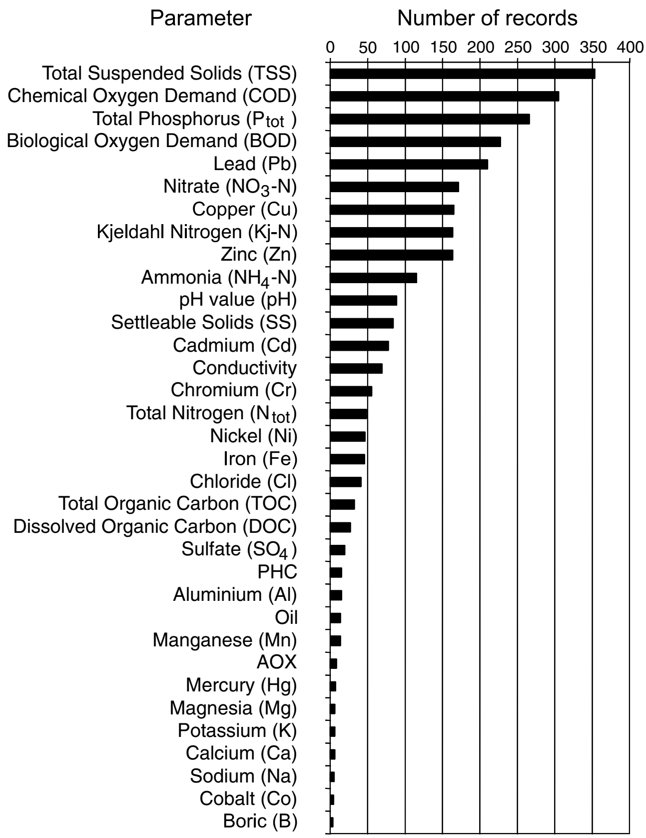

Figure 4 Analysed parameters and number of records in Brombach and Fuchs (2003)

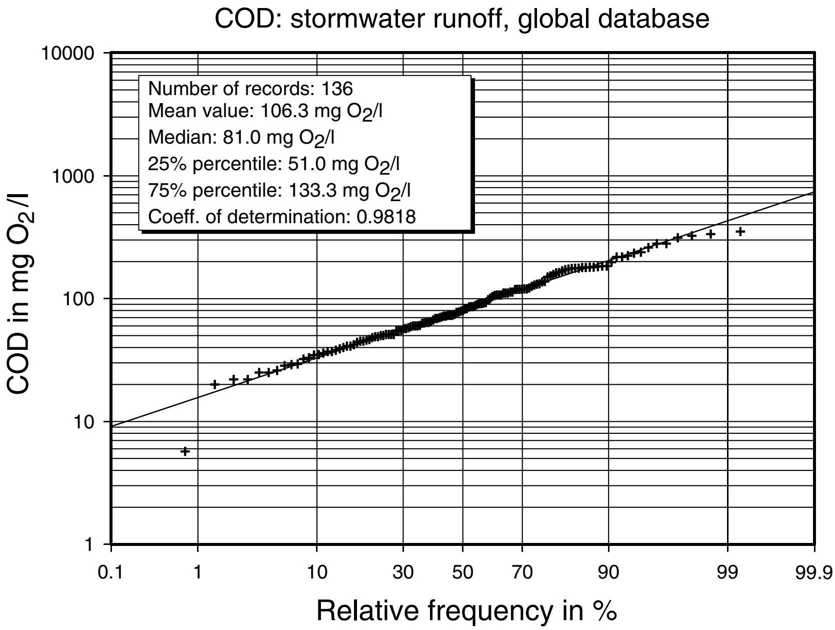

Figure 5 Distribution of measured COD concentrations in storm water runoff of separate sewer systems (example of the data from Brombach and Fuchs, 2003)

Table 3 Median pollutant concentrations for some selected parameters

Median pollutant concentrations	**TSS mg/l**	**SS mg/l**	**BOD mg/l**	**COD mg/l**	**TOC mg/l**	**P_{tot} mg/l**	**NH_4-N mg/l**	**NO_3-N mg/l**
storm sewer, separate system, world	141.0	1.18	13.0	81.0	19.0	0.42	0.80	0.80
overflowing combined sewage, combined system, world	174.5	1.59	60.0	141.0	30.6	1.25	1.94	1.13
WWTP outflow (mean), Germany	7.5	0.0	5.0	32.0	9.2	0.8	2.0	7.8
Reference			ATV-DVWK (2003)	ATV-DVWK (2003)	NRW (2000)	ATV-DVWK (2003)	ATV-DVWK (2003)	NRW (2000)

Median pollutant concentrations	**N_{tot} mg/l**	**Cd µg/l**	**Cr µg/l**	**Ni µg/l**	**Pb µg/l**	**Cu µg/l**	**Zn µg/l**
storm sewer, separate system, world	2.4	2.3	16.0	22.6	118	48.0	275
overflowing combined sewage, combined system, world	12.6	1.4	21.0	12.0	70	97.5	280
WWTP outflow (mean), Germany	9.0	0.2	3.0	7.8	2.6	12.4	46.7
Reference	ATV-DVWK (2003)	UBA (2002)	UBA (2002)	UBA (2002)	UBA (2002)	UBA (2002)	UBA (2002)

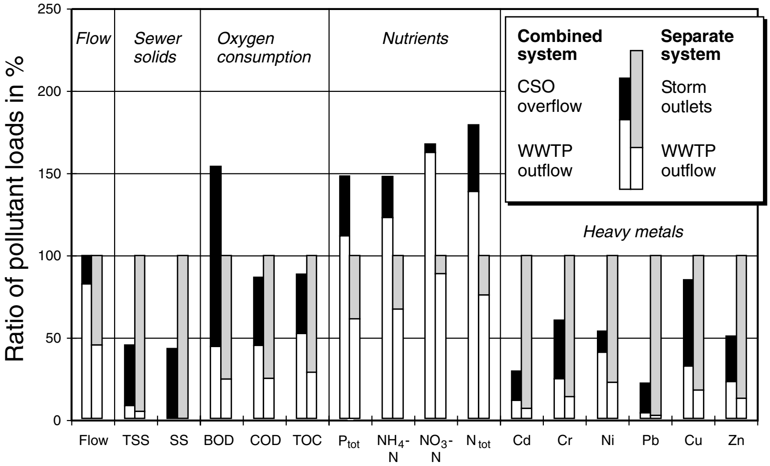

Figure 6 Ratio of pollutant loads; all loads are standardized using the total load (storm outlets plus treatment plant outflow) from a separate system as 100%. The white columns indicate the share of the WWTP outflow load

Results and discussion

A balance of the pollutant loads that are released by both traditional sewer systems is shown in Figure 6. For better comparison, the ratio of loads was plotted rather than the absolute values. As a reference, the total load of a separate system (storm outlets plus WWTP) serves as 100% for any parameter. The white columns in Figure 6 represent the load by the treatment plant outflow. The following observations can be made.

- The total flow input into the receiving waters is, of course, equal for both systems, see the leftmost columns, which total 100%. However, it can be seen that in a combined system, nearly 80% of all runoff is passing the treatment plant while this is less than 50% in a separate system. Because of the different flow, the load by the WWTP outflow is always larger in the combined system than in the separate, due to equal assumed WWTP outflow concentrations.
- For the total suspended and settleable sewer solids, TSS and SS, respectively, the combined system yields considerably smaller pollution loads. For these parameters, the WWTP works nearly ideally, i.e. the TSS and SS concentrations in the outflow are almost zero.
- Concerning the pollutants causing oxygen consumption, the figure reveals that the total COD load of a combined system is only slightly smaller than of a separate. The parameter TOC shows the same behaviour. On the other hand, the BOD load from the combined system is considerably larger than from the separate system. The WWTP efficiency is very good to remove BOD pollutants in both systems, however CSO treatment has limited effects on BOD reduction while the separate storm sewer transports merely small BOD loads.
- The nutrients show an inhomogeneous behaviour. The total nitrogen loads to the receiving waters are much larger with the combined system. The effect is due to the nitrogen, which is bound organically, e.g. in proteins. In the same way as BOD, such substances occur in high concentrations in combined sewage overflow. For ammonia nitrogen NH_4-N, one might suspect a similar performance due to ammonia in urine, but this effect is less pronounced. For all nitrogen parameters, a surprisingly high load is due to the WWTP outflow in both systems. This is due to the fact that nitrogen compounds are less easily degradable. Moreover, aerobic ammonia nitrification and anaerobic nitrate

reduction (denitrification) are interdependent such that ammonia is converted into nitrate and nitrate finally into elementary nitrogen, while this final step is in many cases incomplete. Looking solely on NO_3-N, the mean WWTP outflow concentration is larger than any inflow, i.e. the WWTP efficiency is negative for this parameter.

- Phosphorus load from CSOs in a combined system and in storm outlets of the separate system are in the same magnitude. The total load is, however, more pronounced in the combined system. These observations may be explained by a higher P concentration in combined sewage due to faeces and detergents as major P source, in combination with a comparatively low P removal efficiency due to low microbiological degradation. P removal efficiency is enhanced by phosphate precipitation and other more advanced process steps, however this is not yet done at every German WWTP.
- Of all heavy metals, such as cadmium (Cd), chromium (Cr), nickel (Ni), lead (Pb), copper (Cu) and zinc (Zn), a combined sewer system releases generally much smaller loads than a separate, e.g. for Pb and Cd, less than 30%. This is a considerable reduction. The main source of heavy metals is surface runoff from roads which takes away wear and tear of tyres, brake discs, etc., while sanitary sewage contains generally only small amounts. Under normal pH conditions, heavy metals are non-soluble and attached to settleable solids so that they can be removed by clarifier-type tanks. Obviously, state-of-the-art stormwater treatment in combined systems is very efficient in reducing the heavy metal load. A comparatively high emission of heavy metals is a decisive disadvantage of the separate system, which is usually underestimated. Heavy metals will also form a problem when alternative techniques such as infiltration are applied.

The present investigation is a general approach, which simplifies the effects found in reality considerably. All results are strongly blurred by the data scatter. Further elaboration must be omitted here for brevity. Moreover, the present paper does not account for modifications of separate systems in order to keep low-polluted runoff from the sewer. Infiltration and similar measures will reduce the inflow and also the pollutant load into the receiving waters somewhat, but by shifting the target towards the groundwater. Such modern modified systems require good stormwater treatment to fulfil their promise of good pollutant retention besides their advantage of flow retention and groundwater recharge.

The following consequences for the choice and the design of the drainage system may result.

- The separate system is not generally the one that releases less pollution. The overall picture Figure 6 gives a far more differentiated answer. For a wide range of parameters, particularly for settleable solids, for less easily degradable matter expressed by COD and TOC and for all heavy metals, the combined system reveals considerably smaller total pollution loads to the receiving waters. Furthermore, the separate system is superior for all nutrients including phosphorus, and for BOD.
- Any assessment of the pollution loads into the receiving waters must also account for the treatment plant. The WWTP outflow load is never negligible. For some parameters such as nutrients, it is the most pronounced source of pollution. Improvements in the treatment plant will generally be very effective. However, a "good" treatment plant will generally shift the results in favour of the combined system.
- Stormwater treatment, e.g. by retention and settling tanks, is necessary in both systems. There are doubts on the frequently heard argument that a separate storm sewer will allow to dispense with any stormwater treatment structures. Many existing separate (and combined) systems will need expensive upgrading with retention and settling tanks in the future.
- More efficient stormwater treatment in the future? The concentration data used shows no differentiation with regard to the degree of existing stormwater treatment at the site where

the samples were taken. It can be expected that in modern combined and also separate sewer systems, which feature stormwater treatment, the pollutant concentrations of several parameters will go down and improve the scenario.

- Costs and benefits: The separate system is particularly expensive due to the double sewer. If stormwater treatment has to be implemented additionally to the storm sewer or even to the sanitary interceptor to avoid sanitary sewer overflows (SSO), the overall cost will multiply. These expenses yield some pollutant load reduction, however for some parameters only. General demands on the separate system as a standard solution are thus questionable.
- Finally, some open questions may be mentioned which make the overall result even more complicated, e.g.: What about false cross connections between sanitary and storm sewer in separate systems? What to do with the sludge from stormwater treatment structures in separate systems? Since every project is different, it requires individual investigations including also such collateral effects.

Conclusions

The present investigation is restricted to a simplified load balance for a comparison of the traditional separate and combined sewer systems on the background of German urban drainage practice. The overall result is that neither drainage system is generally "the better one". A typical separate system will release less loads of BOD and particularly of nutrients. A combined system is superior with regard to solids and particularly to heavy metals where a strong load reduction can be shown compared with a separate system. To assess the total long-term pollutant emission into the receiving waters, the treatment plant outflow is to be included generally since it contributes to the total load with a high share, particularly for nutrients.

Any uncritical preference of the separate system as a particularly advantageous solution is thus questionable. Stormwater treatment is needed here in the same way as in the combined system. The cost-benefit ratio of the separate system will get unfavourable. Modified systems with infiltration will improve the features, but there the groundwater is the target of some remaining runoff pollution.

On the other hand, it may be put to discussion whether a traditional combined sewer system which features sufficient CSO storage capacity always deserves disqualification. The system shows fair pollutant retention qualities for most parameters at reasonable construction and operation costs. This should be kept in mind in future discussions on applicable standard solutions for sewer systems.

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