Combined sewer system versus separate system – a comparison of ecological and economical performance indicators

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Abstract This paper aims at comparing the cost-effectiveness of the two main types of urban drainage systems, that is, the combined sewer system and the separate sewer system, based on the analysis of simulations. The problem of which of the two systems is better was heavily discussed over the years and the answer given to the question was usually: 'it depends'. In this work, specific impacts are investigated in terms of a cause–effect analysis. The results are subsequently summarized and can help in the choice of the system to be implemented. Despite earlier reasoning, studies on river water quality strongly indicate that the separate system is not always the preferable solution because the polluted runoff from the street, containing e.g. different heavy metals, is discharged directly into the river. This analysis aims to compare the two different sewer systems on the basis of literature data and simulation of specific cases. The results are evaluated, as suggested in the EU-Water Framework Directive, on the basis of different assessment criteria: river water quality and morphology impacts, emissions and costs.

Keywords Combined sewer system; cost-benefit analysis; performance indicators; separate sewer system; urban drainage

Introduction

In central Europe about 70% of the sewer system is combined (Butler and Davies, 2004). However, at the end of the 20th century it was common practice in many countries to shift to the separate sewer system whenever possible. Reasoning was, on the one side, the absence of combined sewer overflow (CSO) – although replaced with direct stormwater discharge – and on the other hand the easier optimisation possibility of the wastewater treatment plant (less diluted wastewater). But recent studies demonstrated that the separate system is not always the best option for the receiving water quality (Fenz, 2002; Paoletti and Sanfilippo, 2004; Brombach *et al.*, 2005). This paper aims to make a comparison between a combined and a separate system on the basis of simulation results of simplified catchments with different dimensions, with different pollution concentration in the runoff and in the dry weather flow and with different climatic conditions. The consideration of different boundary conditions together with economic consideration makes this paper unique. A further comparison of the drainage option with other technologies (esp. those aiming at sustainable solutions) would be interesting but would exceed the frame of the paper.

Methods

The analysis is based on simulation results where pollution fluxes and hydraulic impacts are computed by means of the software program City Drain (Achleitner *et al.*, 2006). The results were evaluated with Matlab programs specifically created for this analysis. The rain series used for the simulation were 10 years long.

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The catchment's configuration is simple, with one CSO per catchment as long as the reduced area is smaller than 300 ha. For larger catchments, these were subdivided into identical sub-catchments. Overall, the dimension of the catchments is varied between 60, 100, 300, 600 and 1,000 ha impervious area. The population density of the catchment was varied between low population density (70 PE/ha) and high population density (200 PE/ha). The choice of such values is based on data from real case studies. The related dimensions of CSO basin and WWTP inflow are calculated according to the Austrian regulation (ÖWAV-Regelblatt 19, 1987).

The definition of the different wastewater streams is based on a literature review. The concentrations of the different pollutants for the two systems were chosen according to the "ATV DVWK Datenpool 2001", described in (Fuchs *et al.*, 2004). Here concentration data for different pollutants is reported from numerous countries. From this database, the minimum (a), median (b) and maximum (c) values for concentration in dry weather flow and in stormwater are chosen for the simulation.

According to the approach of the European Water Framework Directive (2000/60/EC, 2000), the effectiveness of the sewer system is defined by assessing the impact of the drainage system on the receiving water, using water quality indicators.

Receiving water quality indicators

The receiving water quality indicators are chosen according to five relevant receiving water impact types. Morphological impacts are considered by the indicator erosion frequency, acute toxic impacts by means of the un-ionised ammonia concentration, accumulating impacts by the copper load, impacts on the oxygen abundance by oxygen depleting substances and eutrophication by the nitrogen load (Engelhard *et al.*, 2006a).

The erosion frequency is calculated as the number of overflow events higher than the critical discharge, calculated here for a small river with a mean low water flow $Q = 2\,m^3/s$ (Q_{crit_c} $3.05\,m^3/s$). More details on this procedure can be found in Engelhard *et al.* (2006b). The total loads are calculated as the mean value of all simulation years. The critical oxygen deficit (D_c) is calculated using the Streeter–Phelps formula (BWK, 2001) where the mean low water flow in the river and the BOD concentration are assumed to be the same as the overflow water. This assumption – that essentially neglects the river base flow – is a further simplification of the Streeter–Phelps formula, but makes the equation independent from the river size and thus the results more comparable. The un-ionised ammonia is calculated as the concentration in the river that is achieved at least one hour per year (for the same river type as used for the erosion calculation).

Costs analysis

As suggested by the EU-WFD (2000/60/EC, 2000) the optimal solution is to be evaluated not only from an ecological point of view but also from an economical analysis. To allow for cost comparison of the different system parts, only the costs functions from one literature source, that is, Günthert and Reicherter (2001), are applied:

$c = 197.14\ e^{0.0012x}$ for the pipes, where c is in €/m and x is the diameter of the pipe in mm, and

$c = 2{,}925\ x^{-0.22}$ for the CSO basin, where c is in €/m^3 and x in m^3

The pipe diameter design for the different investigated catchments was calculated using the rational formula according to the Austrian regulation (ÖWAV-Regelblatt 11, Draft 07.2004).

Results and discussion

Different population densities

Figure 1 shows the influence of the population density in the catchment on the performance of combined and separate sewer systems. On the axes the different indicators (see above) are plotted. Each axis has a different scaling, where the factor is noted in the unit. Each value in the figure has to be multiplied with the corresponding factor to obtain the original value. In this figure the factor of the copper load is 0.1. In Figure 1a the copper load in the separate system is 20, which means that $20 \times 0.1 = 2$ tons per year are discharged into the receiving water.

The four catchments shown in the figure above have either 100 ha or 1,000 ha impervious area. Catchments C1 and C9 have a population density of 70 while C2 and C10

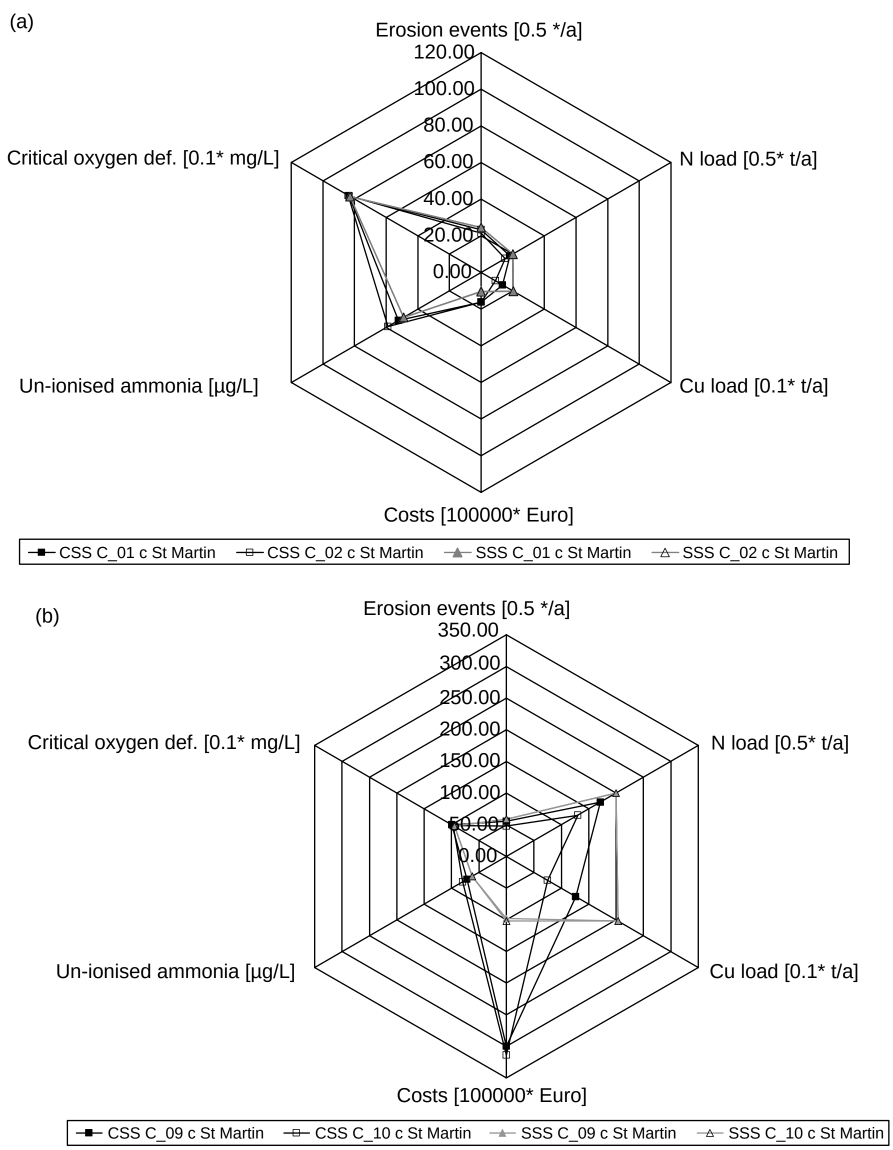

Figure 1 Combined and separate system impacts calculated for a catchment of 100 ha (a) with 70 PE/ha (C1) 200 PE/ha (C2) and of 1,000 ha (b) with 70 PE/ha (C9) 200 PE/ha (C10), respectively. High pollution (concentration c), alpine rain (St Martin, Austria). Note that each axis has a different scaling

have 200 people equivalents (PE) per hectare population density. The pollution concentrations in the stormwater as well as in the dry weather flow are high (concentration c) and the stormwater pollution was assumed to be the same for all catchments independent of the population density. The rain series used for the simulation was the alpine rain from St Martin (Austria).

It can be seen that for the combined sewer system (CSS) in the catchments with lower population density (C1, C9) the yearly discharged loads (copper and nitrogen) and the erosion frequency are higher than in the catchments with higher population density (C2, C10). This is because the interceptor flow capacity to the WWTP is directly related to the number of PE. In contrast, the maximum concentration of un-ionised ammonia and the critical oxygen depletion are higher for the catchment with higher population density.

The erosion frequencies for the separate system are always higher than for the combined system. As expected, the graphs of the separate system are positioned exactly above each other. This shows that the performance of the separate sewer system is (apart from misconnections which are not included in this study) independent of the population density. The costs for the separate sewer system are lower than for the combined system. One obvious reason is that in the combined system a CSO basin is always implemented, whereas in the separate system no treatment is considered here. This configuration was chosen because it is the most common one in Europe.

The influence of the catchment size is investigated in Figure 1b. The difference is mainly due to the fact that the erosion frequency, the critical oxygen deficit and the ammonia concentration depend on the size of the sub-catchment (connected to the CSO) and not on the total catchment area. But the influence of the population density on the performance of the sewer systems is the same: the combined system in the catchment with lower population density discharges higher loads into the receiving water and causes lower ammonia concentration but higher critical oxygen deficits. The performance of the separate sewer system is independent of the population density.

Different rain series

In the following, the influence of the rain characteristics on the receiving water indicators is investigated. The four rain characteristics analysed are (Table 1): MAR = mean annual rain volume; VQR = annual runoff volume (MAR minus losses); NE = number of rain events (an event is defined by a dry weather period of least one hour); ME = maximum rain event once per year.

The analysis reveals (with very few exceptions) the same influence of the rain type. The rain from Copenhagen produced always and for all parameters the lowest impact in the receiving water. The alpine rain from St Martin caused the highest pollution in the receiving water (Figure 2).

A reason for this relation can be found when taking into account the correlation between rain characteristics and performance indicators for the combined system as outlined in the paper (De Toffol *et al.*, 2006). There it was demonstrated that the CSO overflow volume is

Table 1 Characteristics of the rains (MAR: mean annual rain volume; VQR: total runoff volume; NE: number of rain events; ME: maximum rain event once per year)

Gage	Country	MAR [mm/y]	VQR [mm/y]	NE [events/y]	ME [mm]
St Martin	Austria	1,297.60	1,132.35	307.9	52.7
Brussels	Belgium	846.34	660.62	243.0	26.6
Vienna	Austria	680.39	535.09	244.1	39.3
Copenhagen	Denmark	604.09	475.96	198.1	24.4

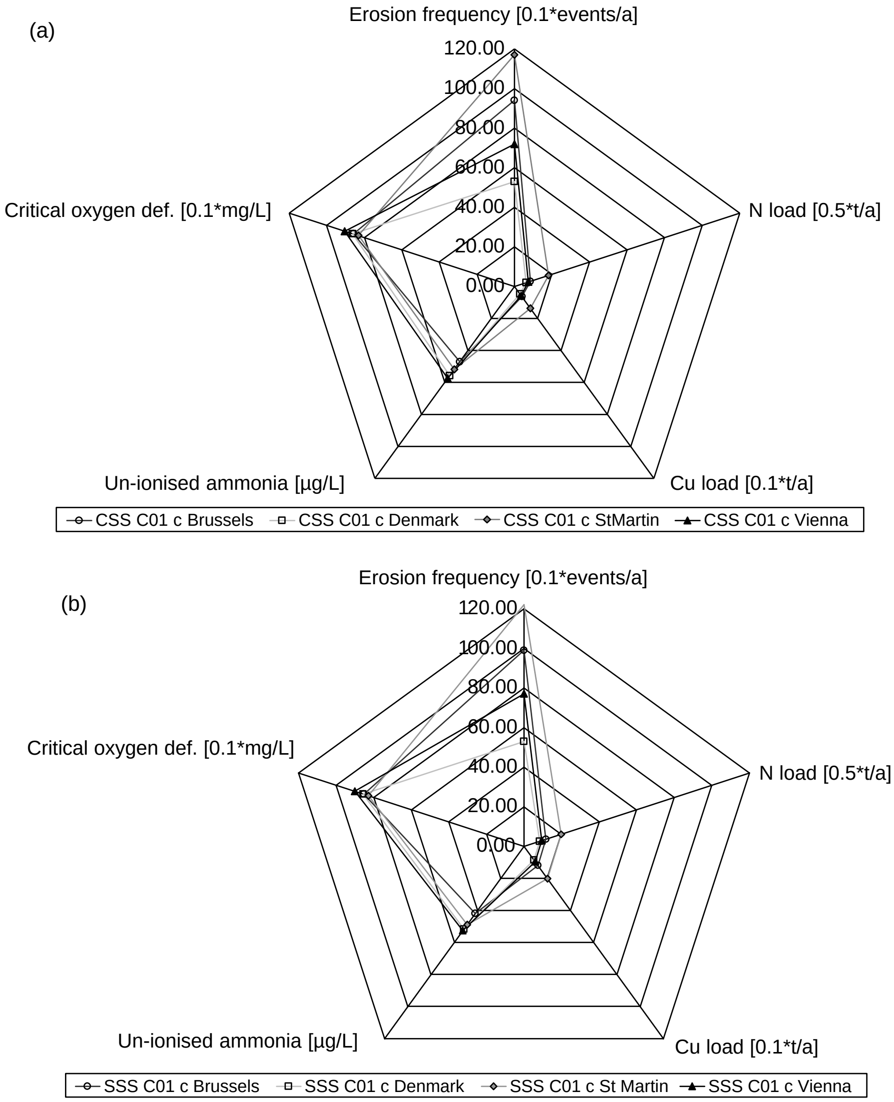

Figure 2 Different types of rain: alpine (St Martin), continental (Vienna) and oceanic (Brussels, Copenhagen), performance of (a) combined system (CSS) and (b) separate system (SSS) in catchment 1 (100 ha, 70 PE/ha) with high pollution (concentration c). Note that each axis has a different scaling

correlated with the mean annual rain volume (MAR). Engelhard *et al.* (2006a), on the other hand, show that the loads and the erosion frequency correlate with the overflow volume. So it can be concluded that the loads are higher where the MAR is higher.

The results above confirm this relation in principle (an exemption is only seen for the indicator copper load). To compare the effects caused from the different rain series a ranking was compiled based on arithmetic assessment of all cases investigated (Table 2). Although the strong influence of the rain characteristics to the sewer system performance is confirmed, the influence remains the same for both combined and separate systems, i.e. none of them is outperforming under these circumstances.

Different pollution concentration

The influence of the pollution concentration in the flow was investigated next. The results show that for the minimum pollution concentration (a) and the median concentration

Table 2 Ranking (1 = best and 4 = worst) of performance indicator values as a result of different rain input series applied to all case studies. Only for copper load separate (italic numbers) and combined systems exhibit different results for Brussels and Viennese rain. Results for acute pollution indicator values show no clear picture and are thus not presented

	Erosion frequency	N load	Cu load
St Martin	4	4	4
Brussels	3	3	2–*3*
Vienna	2	2	3–*2*
Copenhagen	1	1	1

(b) the performance of the combined and separate systems is nearly the same (Figure 3). Only with the highest pollution concentration (c) do obvious differences between combined and separate systems occur.

With high pollution concentration (c) the combined sewer system is performing better than the separate system regarding the discharged loads and the erosion frequency. Regarding acute pollution, i.e. one hour un-ionised ammonia concentration and the critical oxygen deficit, the separate sewer system is better.

With the median pollution concentration the system behaviour is the same as with the high pollution concentration. The combined system discharges lower loads but induces higher one hour un-ionised ammonia concentrations and critical oxygen deficits.

With the minimum pollution concentration the copper load discharged by the combined system is lower but the discharged nitrogen load, the un-ionised ammonia concentration and the critical oxygen deficit caused in the receiving water are higher.

Analysis of the morphologic impacts

Current regulations already provide limitations for the protection of streams from adverse hydraulic impacts. Usually overflow volumes are limited, being linked to extreme flood events, not considering the conditions of the receiving water. A more sophisticated definition for adverse hydraulic impacts is to limit not the hydraulic impact itself but the frequency of erosion events depending on the (biological and morphological) state of the considered river (Rauch *et al.*, 2002).

Figure 4 shows that the combined and the separate system induce a similar number of erosion events per year in the receiving water. For the larger catchments the separate system is even worse than the combined system. In this study it was assumed that the same catchment size as in the combined system is connected to a discharge structure. In reality separate systems could have more discharge structures than combined systems and thus smaller catchments connected to the discharge which leads to smaller overflow volumes and a reduced erosion frequency. A detailed assessment of this relation is given by Lek and Rauch (2006).

Overall evaluation

The general comparison of the performance of combined and separate sewer systems shows that the loads discharged into the receiving water are always higher for the separate system than for the combined system. Although not taken into account here, these loads could be reduced by installing stormwater treatment facilities in the separate system. The ammonia concentration and the critical oxygen deficit are lower for the separate system than for the combined system.

Besides their dependence on the sewer system type and the population density the discharged loads of copper and nitrogen depend on the total catchment size. The maximum

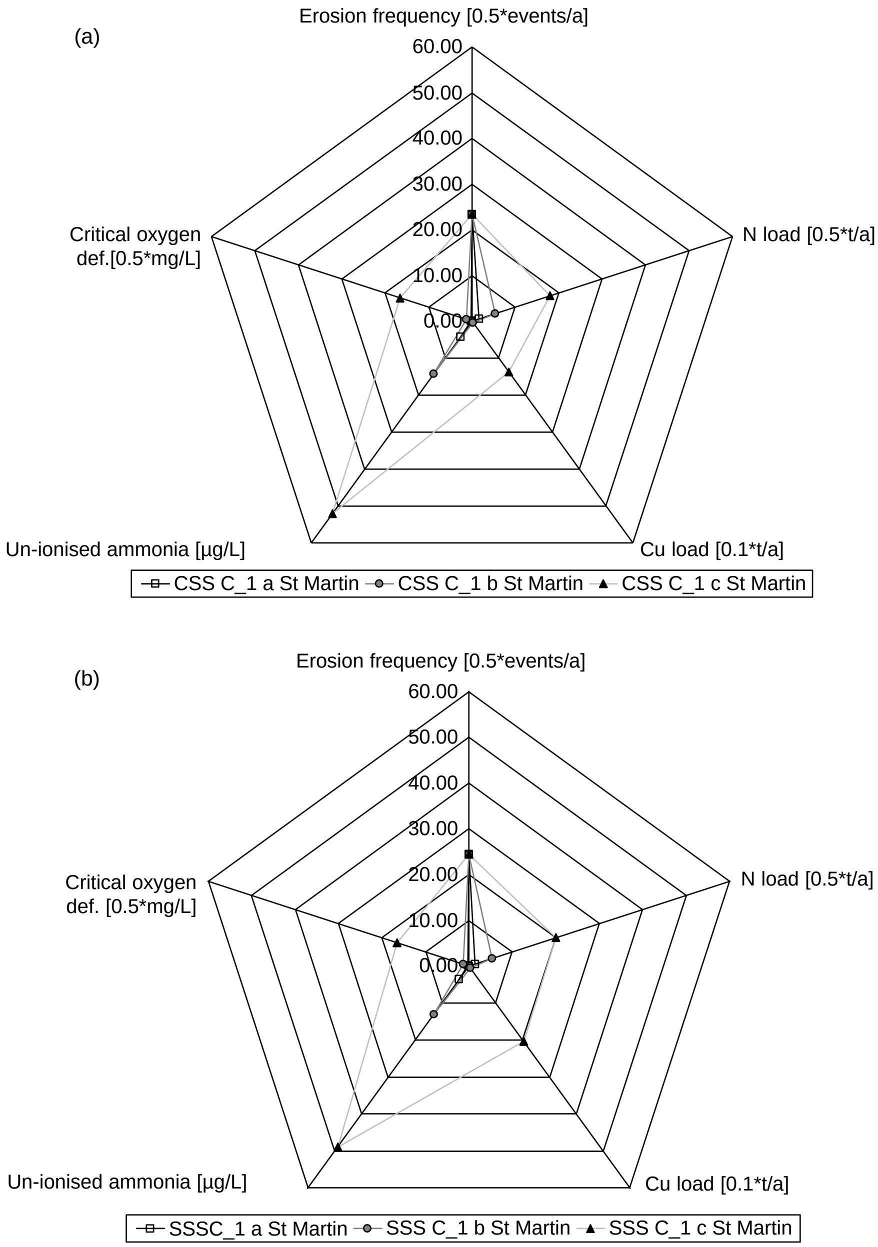

Figure 3 Different pollution concentrations (a- low, b- median, c- high) in stormwater and dry weather flow, performance of combined system (CSS) and separate system (SSS) in catchment 1 (100 ha, 70 PE/ha) calculated with alpine rain (St Martin). Note that each axis has a different scaling

discharge is determined by the size of the sub-catchment connected to the CSO (or directly to the receiving water, respectively in the case of the separate system).

Table 3 reveals that in terms of an overall evaluation (considering all the results together) the separate system works better for river with oxygen depletion and acute toxic impact problems. In all other cases, i.e. both in the case of accumulative pollution impacts and of hydraulic impacts, the combined system is preferable.

The total costs of combined sewer systems as well as separate sewer systems increase with the size of the catchment. The influence of the population density is low: although

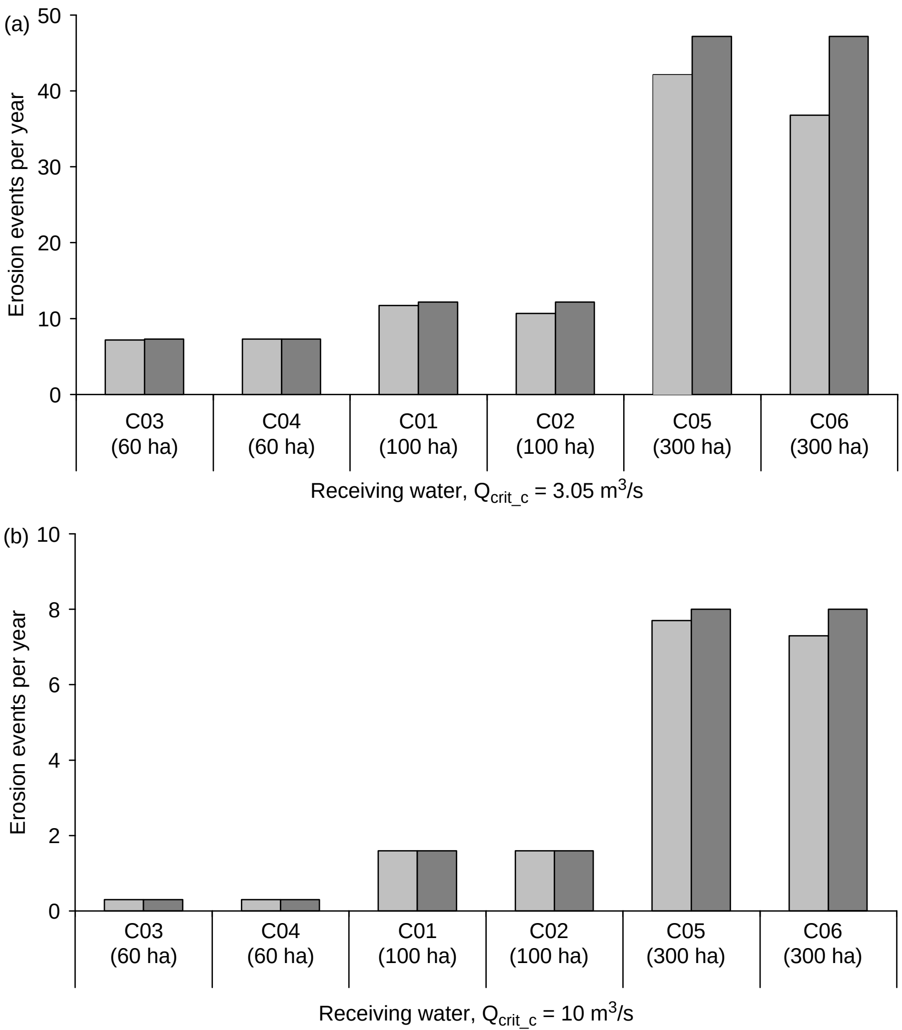

Figure 4 Number of erosion events per year: catchments C1, C2, C3, C4, C5 and C6, erosion frequency in a small receiving water RW with Q_{crit_c} 3.05 m^3/s (left) and a larger RW with Q_{crit_c} 10 m^3/s (right). Alpine rain (St Martin). The lighter colour represents the combined, the darker one the separate system

higher density implies bigger pipe diameters, the construction costs for the storm sewer are dominant so that such variations are negligible when considering the whole system.

The costs for the separate sewer system are lower than for the combined system because there are no basins included. In some countries, treatment of stormwater is

Table 3 Comparison between combined and separate systems based on the results of the calculation on 10 catchments with three different concentrations for both sewer systems, combined and separate. The X represents which system is more adapted in order to reduce the impacts to the receiving water

Overall evaluation			
Impact	**Indicator**	**CSS**	**SSS**
Hydraulic impact	Erosion Frequency	X	
Oxygen depletion	Dc critical oxygen		X
Eutrophication	Nitrogen load	X	
Acute toxic impact	One hour NH_3 conc.		X
Accumulation	Copper load	X	

regulated by design rules (Brunner *et al.*, 1996). In such cases the costs for separate systems will be higher than the values shown here and will also be case specific. In such cases the costs can easily exceed those of combined systems.

Conclusions

In this paper we compared combined versus separate sewer systems based on ecological and economical performance criteria. It was found that

- separate sewer systems discharge considerable pollutant loads *via* their overflow structures into the receiving waters if no stormwater treatment is implemented. Combined systems which are dimensioned according to current design rules (ÖWAV-Regelblatt 19, 1987) discharge lower loads *via* their CSO structures. The ammonia concentration in the discharged water is higher in the combined sewer overflow leading to higher un-ionised ammonia concentrations in the receiving water.
- the magnitude of the impact caused by sewer overflows is controlled by the rain characteristics as certain rain types can amplify the impacts on the receiving water.
- if the pollution concentrations are low, both sewer systems (combined and separate) have a similar performance. But with increasing pollution concentration the environmental impact caused by the separate system is higher than in the combined system.

The choice of the sewer system should therefore be made with regard to the rain characteristics, the pollutant concentration in the catchment and the sensitivity of the receiving water. Generally it can be concluded that the separate sewer system is cheaper if the rainwater is not treated. However, many countries have implemented regulations which enforce stormwater treatment. Depending on the type of treatment applied, the costs for separate sewer systems increase, so that the separate sewer system is then generally more expensive than the combined sewer system. The findings drawn from this investigation could help to avoid wrong solutions in the planning phase and suggest, in other cases, which are the effects to be monitored for proper system evaluation.

Acknowledgements

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