Separate and combined sewer systems: a long-term modelling approach

Giorgio Mannina and Gaspare Viviani

ABSTRACT

Sewer systems convey mostly dry weather flow, coming from domestic and industrial sanitary sewage as well as infiltration flow, and stormwater due to meteoric precipitations. Traditionally, in urban drainage two types of sewer systems are adopted: separate and combined sewers. The former convey dry and wet weather flow separately into two different networks, while the latter convey dry and wet weather flow together. Which is the best solution in terms of cost-benefit analysis still remains a controversial subject. The present study was aimed at comparing the pollution loads discharged to receiving bodies by Wastewater Treatment Plant (WWTP) and Combined Sewer Overflow (CSO) for different kinds of sewer systems (combined and separate). To accomplish this objective, a comparison between the two systems was carried out using results from simulations of catchments characterised by different dimensions, population densities and water supply rate. The analysis was based on a parsimonious mathematical model able to simulate the sewer system as well as the WWTP during both dry and wet weather. The rain series employed for the simulations was six years long. Several pollutants, both dissolved and particulate, were modelled. The results confirmed the uncertainties in the choice of one system versus the other, emphasising the concept that case-by-case solutions have to be undertaken. Further, the compared systems showed different responses in terms of effectiveness in reducing the discharged mass to the RWB in relation to the particular pollutant taken into account.

Key words | mathematical models, separate sewer system, wastewater treatment plant, water quality management

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NOTATION

ADWP	Antecedent dry weather period
AWS	mean annual water supply rate
BOD	Biochemical oxygen demand
COD	Chemical oxygen demand
C_{out}	Suspended solid concentration at sewer network outlet
CSO	Combined sewer overflow
C_u	Copper
C_X	Concentrations of the generic pollutant X
f_X	Conversion coefficients for the X pollutant
J	Catchment average slope
K_H	Acidity constant of the sludge
K_s	Stability constant
K_S	The stability constants of the metal–sludge complex
$L_{dry\text{-}X}$	Dry weather load
NH_4	Ammonia
PD	Population Density
P_{tot}	Total phosphorus
Q	Water flow
Q_{eff}	Effective flow
Q_n	Dry weather flow

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Q_{sewer}	CSO inflow-rate
Q_{th}	Theoretical flow
Q_{WWTP}	Flow passing through the CSO
R	Ratio between dissolved and total metal fraction
r_{d1} and r_{d2}	Dilution coefficients
RWB	Receiving water body
S	Catchment surface
SS	Sewer System
SWT	Storm water tank
t	time
TKN	Total Kjeldahl Nitrogen
TSS	Total suspended solids
WWTP	Wastewater treatment plant
Zn	Zinc
β, ω, α, φ_1, φ_2, φ_3	Fourier series parameters
μ	Average value of the simulated variable
Γ_m	Concentration of the TSS in the activated sludge tank

INTRODUCTION

The Sewer System (SS) and the Wastewater Treatment Plant (WWTP) need to be designed as well as managed as a unit considering their interactions in order to protect the quality state of the receiving water body (RWB) (Rauch *et al.* 2002). Traditionally, two different kinds of SSs have been distinguished: separate and combined. The former convey dry weather flow and wet weather flow separately into two different networks, whereas the latter convey both dry and wet weather flow jointly. The question frequently asked today is whether to go towards more careful separation of different fractions of wastewater or to develop the existing systems, mixing all the waters in the same system. The combined SS enables a mixing of the dry weather flow with the stormwater flow; which causes discharge of part of the untreated dry weather flow together with the stormwater.

The adoption of separate SSs enables the systems to avoid CSO (Combined Sewer Overflow), due to the fact that dry weather flow is conveyed by different conduits. However, the pollutants conveyed by stormwater flow are directly discharged into the RWB if no mitigation measure is provided. At the end of the 20th century, a common trend towards separate sewers was established in an effort to better preserve the quality of the RWB by preventing CSO and to allow for easier optimisation of the WWTP (Gagliardi & Viviani 1983; Brombach *et al.* 2005; De Toffol *et al.* 2007). However, recent studies have demonstrated that separate sewers might not be the best solution with respect to the RWB quality state (Paoletti & Sanfilippo 2004; De Toffol *et al.* 2007). Indeed, generally the choice of one system instead of another is driven by the establishment of a compromise between the following opposing requirements: (i) limiting the flow rate diverted to the WWTP in order to limit possible inefficiency resulting from overload of the plant and (ii) attenuating the detrimental effect of the discharged untreated flow. Paoletti & Sanfilippo (2004), comparing the two systems by means of mass balances, concluded that the separate scheme is worse in terms of impact on the RWB. With a similar approach, Brombach *et al.* (2005) claimed that neither drainage system is generally the better one. A typical separate system will release lower Biochemical Oxygen Demand (BOD) loads, particularly of nutrients (Brombach *et al.* 2005).

Bearing in mind the considerations discussed above, a long-term analysis of total emissions from SSs and WWTPs was performed. The study focused on gaining insights into joint management of the two systems while comparing the performance of the different SSs. Separate and combined SSs were compared using simulations of catchments characterised by different dimensions, population density and water supply rate. The different SSs were analysed on the basis of pollution mass balances, taking into account several pollutants (COD, BOD, TSS, P_{tot}, NH_4, Pb, Cu and Zn). The analysis was based on a parsimonious mathematical model able to simulate the sewer system, as well as the WWTP, during both dry and wet weather. The model took into account the most important phenomena that play a relevant role in urban water quality assessment: build-up/wash-off and erosion/deposition of sewer sediments, biomass washload in the WWTP's bioreactor, variation of the sludge blanket level in the secondary clarifier. The rain series employed for the simulations was six years long. The results confirmed the uncertainties in the choice of one system over the other, emphasising the concept that case-by-case solutions have to be undertaken. Furthermore, the compared systems showed different abilities to reduce the discharged mass of pollutants to the RWB, depending on the pollutant.

METHODS

The mathematical model

This study mainly involved analysis of separate and combined SSs using a purpose-constructed parsimonious model developed in previous studies (see, Mannina *et al.* 2004; Mannina 2005). The model is basically divided into two submodels capable of simulating the main elements of an urban drainage system: the SS and the WWTP. As discussed above, the basic idea is modelling the system considering a parsimonious simplified approach in order to gain simulation speed and limit the number of the model parameters. In fact, the modelling approach employs mathematical algorithms that are as simple as possible in order to limit the number of parameters. More specifically, regarding the SS, a home-made simplified model has been worked out. This model contains two modules: a hydrological and hydraulic module, which calculates the hydrographs, and a solid transfer module, which calculates the pollutographs.

The hydrological and hydraulic module is basically conceptual and simulates the rainfall-runoff processes and the runoff propagation both on the catchment surface and in the sewer network. The hydrograph was evaluated starting from the hyetograph by subtracting the hydrologic losses due to infiltration and surface storage. In particular, the hydrological losses were evaluated by means of a rainfall-runoff coefficient, which considered the infiltration losses. The losses in small ponds were evaluated using a parameter that represents the volume trapped by depression storage; this volume was considered to be concentrated in the first part of the hydrograph. Starting from net rain, the hydrograph was obtained with a rainfall-runoff transformation, considering the entire catchment and sewer network as a complex of two linear reservoirs in series. The solid transfer module reproduces the accumulation and propagation of solids in the catchment and in the sewer network. The main simulated phenomena are build-up and wash-off of pollutants from catchment surfaces and sedimentation and re-suspension of pollutants in sewers. The solid deposition in the sewer during dry weather was evaluated by adopting an exponential law depending basically on the duration of the antecedent dry weather and on sewer network characteristics.

In order to have a realistic and correct approach, the erosion of solids were considered taking into account the cohesive-like behaviour of the solids due to almost their transformations in sewer (Freni *et al.* 2008*a*). In particular, the transport equation proposed by Parchure & Metha (1985) coupled to the bed sediment structure hypothesised by Skipworth *et al.* (1999) was considered to simulate the sediment erosion rate.

Following evaluation of the sewer erosion process, the eroded mass was added to the following: (i) the mass washed from the surface during rainfall events and (ii) the mass present in dry weather flow. Together they define the "initial concentration" of solids in the sewer network. Once the solid mass balance in the sewer was evaluated, the model calculated a maximum transportable concentration, or transport capacity, which depends on flow characteristics (Wiuff 1985). In accordance with Wiuff's theory (1985), hydraulic energetic conditions were taken into account in order to evaluate the quantity of particles transportable by the flow and to distinguish between those transported as bed load and as suspended load.

Once the solid concentrations were evaluated, the model calculated their propagation in order to reconstruct the pollutograph at the outlet of the sewer network, considering a linear reservoir scheme (Mannina 2005). The model was based on the evaluation of TSS because the other pollutants (BOD, COD, P_{tot}, NH_4, Pb, Cu, and Zn) were evaluated as a ratio of the TSS concentration for a set value.

According to the hypothesis discussed above, the BOD, COD, P_{tot}, NH_4, Pb, Cu and Zn concentrations were modelled straightforwardly according to the following relationships:

$$C_X = f_X \cdot C_{out} + \frac{L_{dry-X}}{Q} \qquad (1)$$

where C_X is the concentration of the generic pollutant X, C_{out} is the suspended solid concentration at the sewer network outlet, Q is the flow rate, $L_{dry\text{-}X}$ is the dry weather load and f_X is the conversion coefficient for the pollutant X.

Regarding the simulation of the dry weather period, the Fourier series was employed for both quantity and quality model outputs. In particular, the generic state variable, Y, was modelled according to the following equation:

$$Y = \mu \cdot \left(-\beta \cdot \sin(\omega \cdot (t+\alpha) + \varphi_1) - \frac{1}{2} \cdot \beta \cdot \sin(2 \cdot \omega \cdot (t+\alpha) + \varphi_2) - \frac{1}{3} \cdot \beta \cdot \sin(3 \cdot \omega \cdot (t+\alpha) + \varphi_3) \right) + \mu \quad (2)$$

where β, ω, α, φ_1, φ_2, φ_3 are the series parameters, μ the average value of the simulated variable, and t is the time.

Regarding the WWTP sub-model, the behaviour of the part of the plant composed of an activated sludge tank and a secondary sedimentation tank was taken into account. For the activated sludge tank model, the equations derived from Monod's theory along with mass balances were used in order to reproduce the removal of the BOD.

More specifically, the adopted approach considered the organic substrate equal to the BOD concentration and the active heterotrophic biomass equal to the volatile total suspended solids (Vismara & Butelli 1989). This assumption differs from the commonly used Activated Sludge Models (ASM), which uses the COD fractioning approach, which considers different COD components according to the classification of Henze *et al.* (2000). In cases of scarce data availability and in order to gain simulation speed, simpler approaches are preferable to the ASM, because it tends to be overparameterised, and some assumptions, mainly based on literature data, have to be adopted in order to estimate the different COD components (biodegradable, non-biodegradable, active biomass, etc.; see also, Freni *et al.* (2008*b*) and Mannina (2005)).

The sedimentation tank was simulated using the solid flux theory according to the methodology proposed by Vitasovic (1989). The WWTP sub-model allows for evaluating the variations of treatment performances during also storm event. In particular, in the latter case, the increase of flow rates and TSS causes a reduction in treatment efficiency, both regarding the activated sludge tank and the sedimentation tank. This fact can cause TSS overflow and consequent discharging into the RWB. For the simulation of the metals, the model proposed by Wang *et al.* (2003) was employed. More specifically, according to this modelling approach, two metal fractions are distinguished: a dissolved and particulate one. In order to simulate the two fractions, the relation between the dissolved and the total metal fraction is evaluated according to the following Equation (Wang *et al.* 2003):

$$\mathrm{R} = \frac{K_H K_S \Gamma_m \mathrm{SS}}{K_H K_S \Gamma_m \mathrm{SS} + [\mathrm{H}^+] + K_H} \quad (3)$$

where K_H is the acidity constant of the sludge, K_S the stability constant of the metal–sludge complex, Γ_m the concentration of the TSS in the activated sludge tank and SS the inflow of suspended solids to the WWTP.

The sedimentation tank performance was simulated using the solid flux theory according to the methodology proposed by Takács *et al.* (1991). In particular, the solids concentration profile was obtained by dividing the settler into 50 horizontal layers of constant thickness. Within each layer the concentration was assumed to be constant and the dynamic update was performed by imposing a mass balance for each layer. The number of the layers was increased from 10, which is the commonly employed number of layers in the applications, up to 50, since it yielded better model performance results (Mannina 2005). The model equations were resolved considering the difference scheme according to the Runge-Kutta 4 method.

Ancillary structures modelling approach

The model is able to take into account the insertion of mitigation measures in the SS, both structural and non-structural (Freni *et al.* 2005). Among the structural mitigation measures in the study, a trap storm tank (ST) was considered. Storage tanks were simulated by a non-linear reservoir approach. As the purpose of the present paper was connected with receiving water quality mitigation, simulated tanks operated as catch basins able to isolate the first part of the inflow hydrograph until their saturation. More specifically, when the discharge exceeded a fixed threshold value compatible with the WWTP, a weir overflow device diverted the exceeding discharge into the tank. The water level in the tank rose until the maximum capacity was reached. When the tank was full, the previously described overflow device diverted the exceeding discharge to the RWB, thus by-passing the tank. Overflow structure efficiency was taken into account, considering that the discharge to the WWTP could not be considered fixed during rainfall events because of well-known hydraulic energy issues (Butler & Davies 2000). This aspect was considered by assuming an

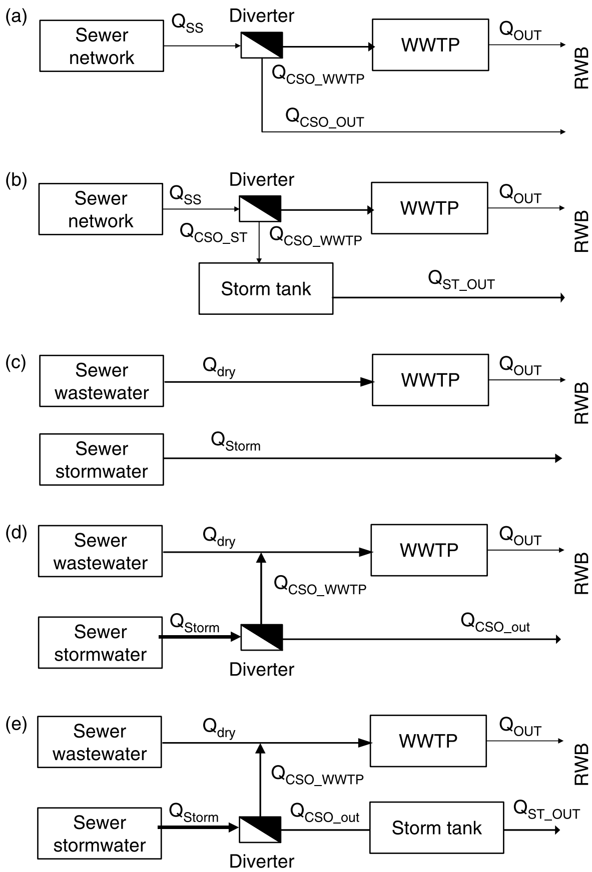

Figure 1 | Simulated SS schemes; (a) and (b) for combined SSs and (c), (d) and (e) for separate SSs.

asymptotic exponential profile and a superior limiting discharge. In particular, the following equation was employed for straightforward CSO modelling (Mannina 2005):

$$\begin{cases} r_d = \frac{Q_{WWTP}}{Q_n} = \frac{Q_{sewer}}{Q_n} & Q_{sewer} \leq Q_{th} \\ r_d = \frac{Q_{WWTP}}{Q_n} = r_{d1} + (r_{d2} - r_{d1}) \cdot \left(1 - e^{\left(\frac{r_{d1} - Q_{sewer}/Q_n}{r_{d2} - r_{d1}}\right)}\right) & Q_{sewer} > Q_{th} \end{cases} \quad (4)$$

where Q_{WWTP} is the flow passing through the CSO and generally represents the WWTP inflow, Q_n is the dry weather flow, Q_{sewer} is the CSO inflow-rate, r_{d1} and r_{d2} are the dilution coefficients and Q_{th} and Q_{eff} are the maximum and the minimum constant value of the flow passing through the CSO, respectively. Q_{th} is the theoretical flow, while Q_{eff} is the effective flow. Q_{th} represents the condition of ideal CSO working conditions, i.e., when the flow rate is greater than an established value the flow rate discharged downstream is constant. In particular, if the surface of the flow passing through the CSO is below the crest of the weir, flow continues to the WWTP only; as the flow rate increases, so does the level of the water surface, providing an increase in the hydraulic gradient along the pipe continuing to the WWTP. According to the definition, the values of Q_{th} and Q_{eff} were evaluated by the following equations:

$$Q_{th} = r_{d1} \cdot Q_n \quad (5)$$

$$Q_{eff} = r_{d2} \cdot Q_n \quad (6)$$

It should be stressed that generally r_{d1} and r_{d2} range from 3 up to 4 and from 6 up to 10, respectively. Here the values were set at $r_{d1} = 3$ and $r_{d2} = 5$.

SIMULATION

Schemes of separate and combined urban drainage systems

The comparison between separate and combined SS was carried out considering five different SS schemes (Figure 1). More specifically, two combined SS schemes and three separate SS schemes were considered. The combined SS schemes (Figure 1a and b) considered a total flow rate coming from the sewer network Q_{SS}, a WWTP inflow rate

Table 1 | Adopted rainfall series characteristics

	1994	1995	1996	1997	1998	1999
Rainfall depth [mm]	285	552	655	602	634	582
N° Events (Vrain > 2 mm)	22	56	63	73	66	57
Average ADWP [days]	5.5	4.5	3.8	4.3	4.1	4.6
Average rainfall intensity [mm/h]	7.2	8.5	9.7	7.7	5.8	6.2
Maximum 5 min rainfall intensity [mm/h]	37.8	42.2	57.8	36.5	40.2	42.8

Table 2 | Reservoir constant values

S [ha]	60	100	300	600	1000
K [min]	15.49	18.25	25.97	32.44	38.22

Q_{CSO_WWTP}, an outflow WWTP Q_{OUT} and an untreated flow rate discharged to the RWB. Furthermore, the untreated flow rate was either directly discharged to the RWB, as in the case of Figure 1a (Q_{CSO_OUT}), or stored in part in an ST (Figure 1b). In the latter case case, an inflow and outflow ST flow rate, Q_{CSO_ST} and Q_{ST_OUT}, respectively, were evaluated. Regarding the separate schemes, since the dry weather flow and the stormwater flow rate, Q_{dry} and Q_{storm}, respectively, were conveyed by two different networks, a limitation of the WWTP inflow rate was established. However, in order to mitigate the detrimental effect of the untreated flow, a part of such flow could be diverted to the WWTP, as in the scheme shown in Figure 1d, and the remaining flow could be directly discharged into the RWB or stored in an ST (scheme Figure 1e). In particular for the present application, as a design criterion for the ST a total specific volume of 50 m^3/ha_{imp} was considered. Concerning the WWTP design criteria, for the activated sludge tank, a food to microorganism ratio of 0.1 kg BOD/kg SS $*$ d and a mixed liquor suspended solids of 3 kg TSS/m^3 were assumed. The sedimentation tank design was carried out assuming an average overflow rate of 1.1 m/h, a sludge recycle flow equal to the average dry weather flow, and a maximum solids loading rate of 5 kg SS/m^2 $*$ h. The size of the WWTP was changed according to the dry weather flow, which is a function of the Population Density (PD) as well as catchment area.

Experimental data

As discussed above, a continuous long-term analysis was carried out in order to compare the different analysed SS schemes. More specifically a six-year rain series was used. The main features of the rain data are summarised in Table 1. In particular, the rainfall data were collected from 1993 to 1999 with a tipping bucket rain gauge and data logger at a maximum time resolution of 1 sec (Aronica & Cannarozzo 2000).

The model simulation was carried out with different catchment surfaces (60, 100, 300, 600 and 1,000 ha of impervious area) and different PDs (70, 100, 150 and 200 Population Equivalents/ha (PE/ha)). Since diverse catchments were considered and the SSs were modelled by means of the reservoir-modelling approach, different values of the reservoir constants were employed as a function of the catchment area according to the following Equation (Ciaponi & Papiri 1992):

$$K = 3.14 \cdot S^{0.321} \cdot J^{-0.234} \quad (7)$$

where S is the catchment surface and J its average slope. In Table 2 the employed values of the reservoir constants are shown for the different catchment areas.

As discussed above, the model simulated the TSS and other pollutants as a correlation (Equation (1)). More specifically, in Table 3 the adopted coefficients derived by previous studies in the literature are reported (Bromach *et al.* 2005; Gasperi *et al.* 2005; Engelhard *et al.* 2008).

Dry weather was modelled using the Fourier series. The coefficients of the series were evaluated considering the records obtained from a literature review (Ciaponi *et al.* 2002; Copp 2002); in Table 4 the adopted values are reported.

In Table 5 the main model parameters employed for the present application are reported. These values were assumed representative of the average conditions for the analysed schemes. This approach is consistent with previous studies (Lau *et al.* 2002; Calabrò & Viviani 2006; De Toffol *et al.* 2007; Fu *et al.* 2008) and can be considered

Table 3 | Mean dry weather concentration values and correlation coefficients

	TSS	BOD_5	COD	NH_4	P	P_b	Zn	Cu
Dry weather mean value [mg/L]	162.94	266.34	373.43	29.85	4.5	32.5	231.5	58.25
Wet weather–conversion coefficient f_X	1	0.51	1.21	0.30	0.0054	0.0001	0.0007	0.0007

Table 4 | Fourier series parameter values

Variables	β	ω	α	φ_1	φ_2	φ_3
Quantity	0.58	0.25	0.39	4.89	7.27	7.92
Quality	0.52	0.24	0.27	4.03	5.76	6.26

acceptable due to the fact that the goal is to make a comparison among schemes assuming similar conditions for each of them.

RESULTS AND DISCUSSION

In Figure 2 the mass balances for the different simulated pollutants are reported. In particular, the pollutant masses per unit of surface and year, normalised to the values of the separate schemes (M_i, i = the simulated pollutant), are plotted with respect to PD. The results concern the case of a catchment surface of 60 ha and a mean annual water supply rate (AWS) of 250 L/PE $*$ d. In Figure 3 the pollutant masses per unit of surface and year, normalised with respect to the value of the separate schemes, are plotted with respect to different catchment areas. The results refer to a population density of 150 PD/ha. The results from other conditions are similar to those shown here and are not reported for the sake of brevity.

In Figures 2 and 3, the masses can be divided into two contributions: the mass discharged without treatment from the CSO, the separate sewer or the ST overflow (column A) and the mass discharged by the WWTP (column B). The total mass for each scheme is also reported (column C).

Analysing Figure 2 the following observations can be made:

- The separate SS schemes always exhibit higher discharged mass, both for particulate and dissolved pollutants, independent of the PD. Furthermore, with increasing PD there is an increment in the discharged mass.
- The total mass coming from the separate SSs does not depend on the PD, while there is a decreasing value of the total mass with CSO for both separate SS and combined SS. Such results are basically due to the diverter, since the interceptor flow capacity of the

Table 5 | Main values of the model parameters

	Parameter	Symbol	Unit	Value
SS	Initial hydrological losses	W_0	mm	0.3
	Catchment runoff coefficient	Φ	–	0.4
	Catchment reservoir constant	K_1	min	Variable
	Sewer reservoir constant	K_2	min	Variable
	Daily accumulation rate	Accu	kg/(ha $*$ d)	8
	Decay rate in the Alley-Smith model	Disp	d^{-1}	0.07
	Wash-off coefficient	Arra	mm^{-1}	0.18
	Wash-off factor	Wh	–	0.64
	Erosion coefficient	M	g/s	108
	Sewer suspension delay	Ksusp	h	0.07
	Sewer bed transport delay	Kbed	h	0.3
	CSO first dilution factor	r_{d1}	–	3
	CSO second dilution factor	r_{d2}	–	5
WWTP	Yield coefficient heterotrophic biomass	μ	h^{-1}	0.0137
	Decay velocity of heterotrophic organisms	kd	h^{-1}	0.00096
	Substrate removal coefficient	ν	h^{-1}	0.0274
	Maximum (practical) settling velocity	ν_0'	m/h	4.17
	Maximum (theoretical) settling velocity	ν_0	m/h	6.04

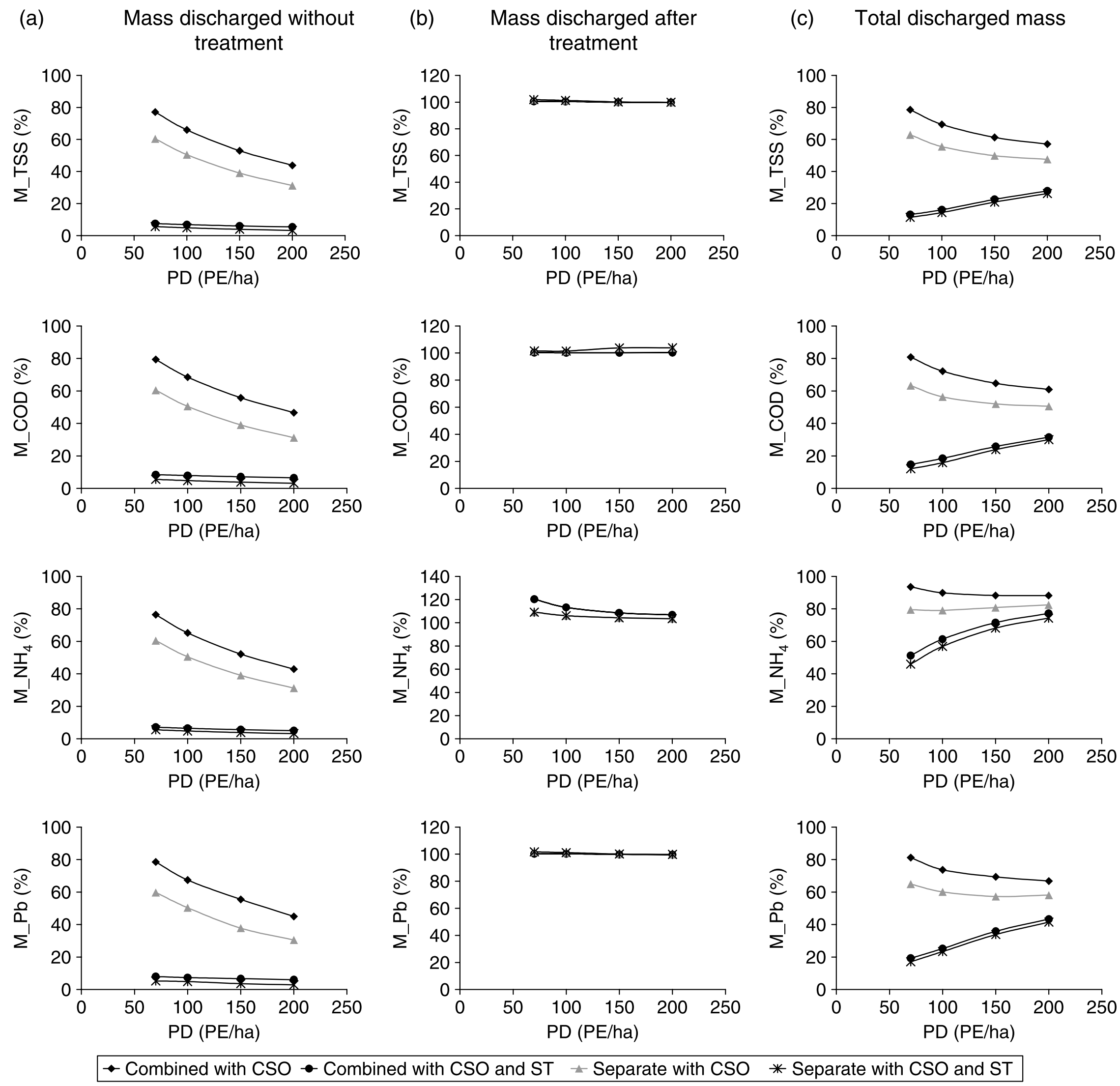

Figure 2 | Normalised discharged pollutant mass vs Population Density for TSS, COD, NH_4 and Pb (AWS = 250 L/PE $*$ d^{-1}).

WWTP is directly related to the dry weather flow and, therefore, to the PE. Since the dry weather flow increases with PD, a higher amount of the pollutant mass and flow volume is diverted to the WWTP, thus increasing the PD. On the other hand the total treated mass discharged by the WWTP increases with PD as a consequence of a corresponding increment in the inflow mass.

- Separate and combined SS schemes with CSO and ST are similar in that the total mass discharged into the RWB is almost the same, although the combined scheme presents a slightly higher pollutant discharged mass.
- The RWB quality state is strictly influenced by the continuous discharges, i.e., those coming from the WWTP, rather than only by intermittent ones. Indeed, the WWTP outflow mass is generally not negligible compared to the total one. Further, the WWTP outflow mass does not vary with the SS schemes apart for some pollutants (BOD, NH_4).
- The normalised mass for all the analysed schemes tends to an asymptotic value that changes in relation to the analysed pollutant. This result could be due to the fact that the different schemes exhibit similar behaviour with different PDs. However, the performance of each scheme

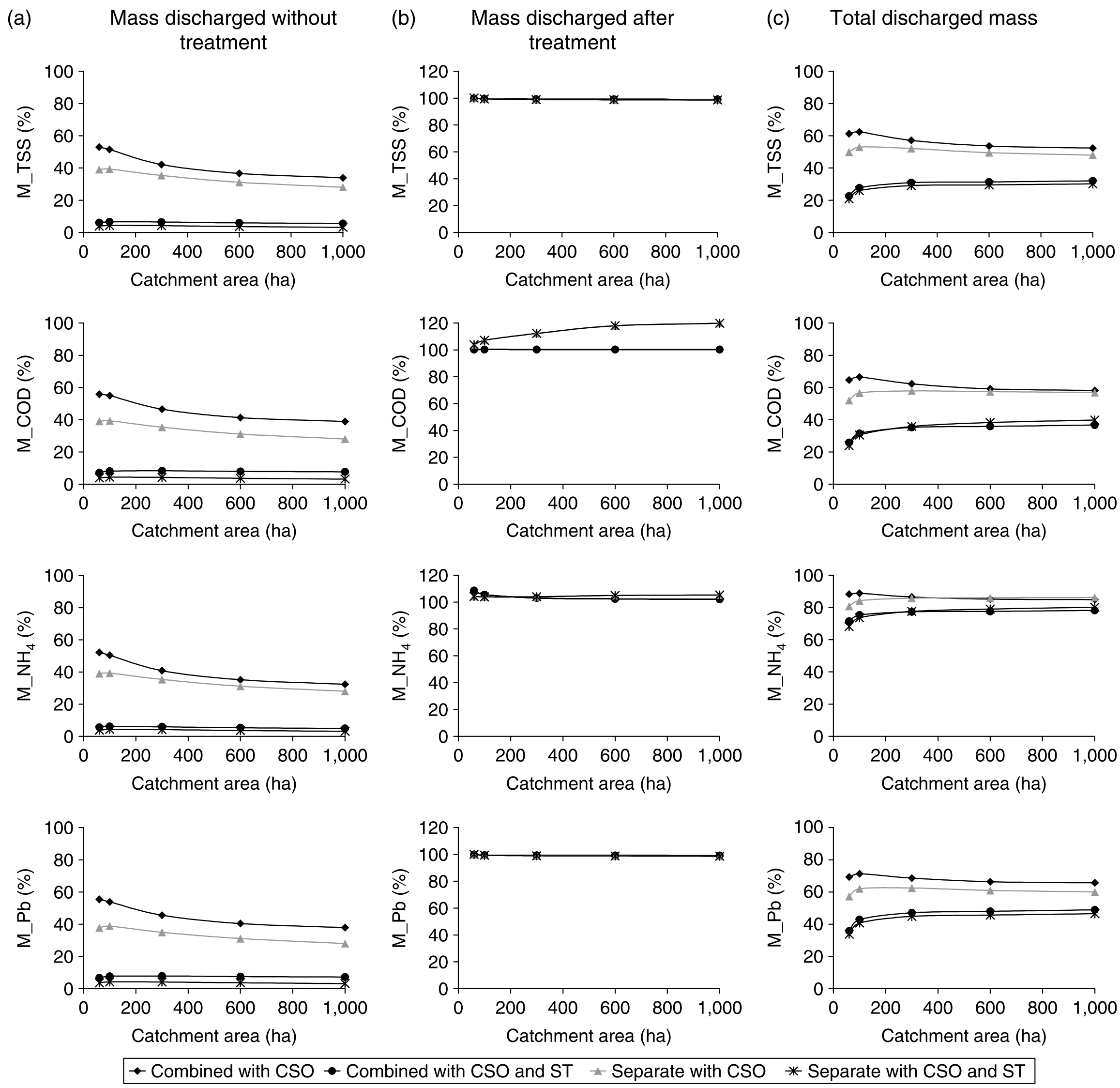

Figure 3 | Normalised pollutant mass discharged vs catchment area (AWS = 250 L/PE ∗ d^{-1}).

is still better than the separate one. These results are probably due to the fact that increasing the PD increases the flow rate discharged to the WWTP, thereby leading to a reduction in the untreated flow rate.

In Figure 3, the normalised discharged pollutant mass versus catchment area is reported. The following comments can be made:

- The separate scheme shows higher pollutant masses for the analysed catchment area ranges.
- For the schemes without STs, the increases in catchment area cause decreases in normalised pollutant mass discharged without treatment. This result is likely due to the higher smoothing effect of the sewer network with increasing catchment area.
- The mass discharged without treatment for the schemes with STs does not change with an increase in the catchment area. Similarly, the mass discharged after treatment does not vary with the catchment area. However, the latter increases up to 20% for some pollutants (COD and BOD) for high catchment areas.
- The influence of the catchment area on the formation of pollutant loads is generally less relevant than the

influence of variations in PD (considering an equal catchment area). Therefore, PD is an important factor to consider in the choice of a better sewer system.

CONCLUSIONS

In this paper a comparison between separate and combined sewer systems was performed. More specifically, five schemes were compared, taking into account the introduction of stormwater mitigation measures. The analysis provided the following insights:

- A separate sewer system is worse in terms of total pollutant mass discharged into the RWB for both continuous and intermittent discharges. Indeed, separate sewer systems discharge considerable pollutant loads via their overflow structures into the RWB if no stormwater treatment is implemented (De Toffol *et al.* 2007).
- Separate and combined sewer system schemes with CSO and STs exhibit a similar behaviour: the total mass discharged into the RWB is almost the same, although the combined scheme discharges a slightly higher mass.
- Mitigation measures (e.g., retention and settling tanks) enabling some reduction of the discharged pollutant mass in both systems and stormwater treatment are necessary.
- The total discharged mass decreases with PD. This result stresses the importance adopting unitary systems, especially in the case of urban systems characterised by large populations. Catchment area shows only a weak influence on discharged mass. Therefore, PD is the key parameter in the choice of sewer system.
- The total WWTP outflow pollutant mass is generally not negligible and it has to be taken into account in order to evaluate the RWB quality state. Indeed, the WWTP-discharged total mass for some pollutants is almost 50% of the total discharged mass. Stormwater treatment for both separate and combined sewer systems is necessary in order to limit the pollutant load discharged into the RWB.

The role played by particulate and dissolved pollutants should be better addressed by considering the fractioning of the different components. More specifically, the reactions taking place in the sewer, which can be considered to be a biological reactor, should be analysed. Better fractioning of the different pollutants should better highlight the differences between the analysed pollutants. Indeed, the SS modelling approach used in this study, which simulated pollutants based on a correlation with TSS, likely causing a bias in the predicted behaviour of the pollutants.

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