Dynamics of pollutant discharge in combined sewer systems during rain events: chance or determinism?

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ABSTRACT

A large database of continuous flow and turbidity measurements cumulating data on hundreds of rain events and dry weather days from two sites in Paris (called Quais and Clichy) and one in Lyon (called Ecully) is presented. This database is used to characterize and compare the behaviour of the three sites at the inter-events scale. The analysis is probed through three various variables: total volumes and total suspended solids (TSS) masses and concentrations during both wet and dry weather periods in addition to the contributions of diverse-origin sources to event flow volume and TSS load values. The results obtained confirm the previous findings regarding the spatial consistency of TSS fluxes and concentrations between both sites in Paris having similar land uses. Moreover, masses and concentrations are proven to be correlated between Parisian sites in a way that implies the possibility of some deterministic processes being reproducible from one catchment to another for a particular rain event. The results also demonstrate the importance of the contribution of wastewater and sewer deposits to the total events' loads and show that such contributions are not specific to Paris sewer networks.

Key words | combined sewer, concentration, mass, sources, spatial coherence, turbidity

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INTRODUCTION

Many studies have been conducted over the last 40 years to examine pollutant fluxes in urban wet-weather discharges (UWWD) (Suarez & Puertas 2005; Schilperoort 2011; Gasperi *et al.* 2012), to determine their temporal and spatial variations (Lee & Bang 2000; Kafi *et al.* 2008) and to describe their entry into combined sewer systems (Gromaire-Mertz *et al.* 1999). These studies globally assess the importance of pollutant fluxes in UWWD and provide information on the characteristics and origins of pollutants (Gasperi *et al.* 2010). Current studies also describe, although rather approximately, pollutants' generation and transport processes (Ashley *et al.* 1999). The results show that both pollutant concentrations and fluxes vary greatly not only during event but also between events.

Yet, Kafi *et al.* (2008) have observed some similar behaviours, as regards fluxes and concentrations of total suspended solids (TSS) (also concentrations of other parameters: chemical oxygen demand (COD), biological oxygen demand after 5 days (BOD$_5$), metals …), among six

catchments, covering land areas varying from 41 to 2,581 ha and containing quite similar land uses.

However, these previous results, specifically the spatial homogeneity, were obtained using a small set of rainfall event data recorded using conventional sampling methods (only a limited number of samples per event and only some events can be sampled). More recently, continuous turbidity measurements have allowed the recording of a time series in either dry or wet weather conditions. These measurements are representative of the present TSS (principal carriers of contaminants) when transformed into TSS concentration using an average TSS–turbidity relationship on different time-scales (Lacour *et al.* 2009; Hannouche *et al.* 2011; Metadier & Bertrand-Krajewski 2012).

The French observatories in the urban hydrology SOERE URBIS system (a long-term observation system for research and experimentation on urban environment) are composed of OPUR-Paris (Observatory of Urban Pollutants in Île-de-France/Paris region), OTHU-Lyon (Field Observatory for

Urban Water Management in Lyon-France) and ONEVU-Nantes (Observatory of Urban Environments of Nantes-France). They provided some statistically representative databases for water flow and turbidity measurements at the outlet of two catchments in Paris (Quais and Clichy) and one in Lyon (Ecully). The aim of this paper is to assess the variability of TSS fluxes and concentrations observed at the outlet of these catchments during both wet and dry weather periods using the SOERE URBIS database records. Results obtained on sites with similar or different characteristics are then compared.

EXPERIMENTAL DATA

Description of the sites

Two experimental catchments in Paris-France, called Quais and Clichy, are monitored within the framework of the OPUR research program. The OPUR program addresses the generation, the transport and the treatment of pollutant loads due to urban water discharges. Both catchments are located in a downtown densely urbanized area and are served by a combined sewer system. The main characteristics of both catchments are displayed in Table 1. The Quais catchment is totally embedded in the Clichy catchment, which implies that the variables observed at the outlet of both catchments are partly redundant. To neutralize this redundancy, volume, mass and concentration are assessed for the complementary fraction of the Quais catchment inside the Clichy catchment (denoted Outside Quais). Data treatment processing, then, consists of subtracting the masses and volumes observed in Clichy and Quais for the same rainfall event.

The Paris sewer system is known for its high deposit level. Deposit contribution to TSS load during rain events is assessed at more than 40% (Gasperi *et al.* 2010).

We also use the data available at the 'INSA of Lyon' for the catchment area of Ecully as part of the OTHU research program (Metadier & Bertrand-Krajewski 2012). In comparison with both Paris sites, Ecully's characteristics are quite different: low population density, residential area with steep slopes, and no street cleaning. Moreover, there is no place of coarse deposit accumulation observed in the Ecully combined sewer system (Metadier & Bertrand-Krajewski 2012).

Equipments and available data set

Both Paris sites are equipped with two redundant turbidity sensors (Ponsel brand with attenuation at 880 nm, calibration using formazine and a range = 0–2,000 FAU), a conductivity sensor (Ponsel brand) and a flow-rate sensor (CR2M SAB600 model, ultrasonic time-of-flight flowmeters). The turbidity sensors are automatically cleaned every 15 minutes and manually cleaned and maintained every second week. The zero-drift and endpoint calibration is also verified. For each site, the final turbidity signal was derived from both available signals once their consistency had been verified. Turbidity, conductivity and flow rate were recorded every minute on both sites during all the rainfall events in 2006. Data have been processed and validated by (Lacour *et al.* 2009).

Storm events are identified using flow rate and conductivity data. The beginning of the event is given by the rise of the flow rate and a sharp drop in the conductivity signal whereas the end of the event is given by the return to the dry weather conductivity. During the year 2006, 74 rainfall events have been identified for Quais and 88 for Clichy, among which 70 events occurred simultaneously on both

Table 1 | Main characteristics of the studied sites

Catchments	Quais	Clichy	Outside Quais	Ecully
Land use	Dense urban	Dense urban	Dense urban	Residential
Surface area (ha)	402	942	540	245
Runoff coefficient (–)	0.64	0.68	0.71	0.15
Active surface[a] (act.ha) (ha)	257	641	383	37
Median slope (%)	0.14	0.10	0.11	2.7
Equivalent inhabitant (EI) BOD_5 (EI^b/act.ha)	600	680	730	220
Average dry weather daily flow (l/(EI·day))	450	400	375	380

[a]Active surface = runoff coefficient × surface area.

[b]EI for biological oxygen demand after 5 days (BOD_5) corresponds to 60 g BOD_5/(inhabitant·day).

Table 2 │ Main rainfall characteristics of the identified rain events on Quais and Clichy

	Rain depth (mm)	Mean intensity (mm/h)	Max 5-min rainfall intensity (mm/h)	Rain duration (h:mn)	Previous dry period (day)
d_{10}	1.2	1.0	2.3	0:30	0.26
Median	4.5	1.8	8.8	1:40	1.41
d_{90}	11.7	6.4	61.6	9:10	5.63

d_{10}: first decile; d_{90}: ninth decile.

catchments (Quais and Clichy, see Table 2). Furthermore, we identified 221 complete dry weather days for Quais and 215 for Clichy, including 209 days common to both sites.

On the Ecully site, flow (measured by a Nivus OCMPro), turbidity (Lange brand, nephelometry at 860 nm, calibration using formazine and a range = 0–4,000 FNU), and conductivity (Yokogawa brand) data were measured between 2004 and 2008 every 2 minutes. During this period, Metadier & Bertrand-Krajewski (2012) validated these data for 239 rainfall

events and 180 dry weather days. This second data set is used for comparison with the results of both Paris sites.

In the following section, turbidity values are transformed into TSS concentrations by applying an average calibration curve as described by Hannouche *et al.* (2011) and Metadier & Bertrand-Krajewski (2012).

RESULTS AND DISCUSSION

Volumes, masses and concentrations at the level of rainfall events and dry days

Distributions

Sewage flow volume, TSS mass and discharge-weighted mean concentration of TSS for both the rainfall events and the dry weather days are illustrated for all the studied catchments in Figure 1 by using Tukey box plots. This
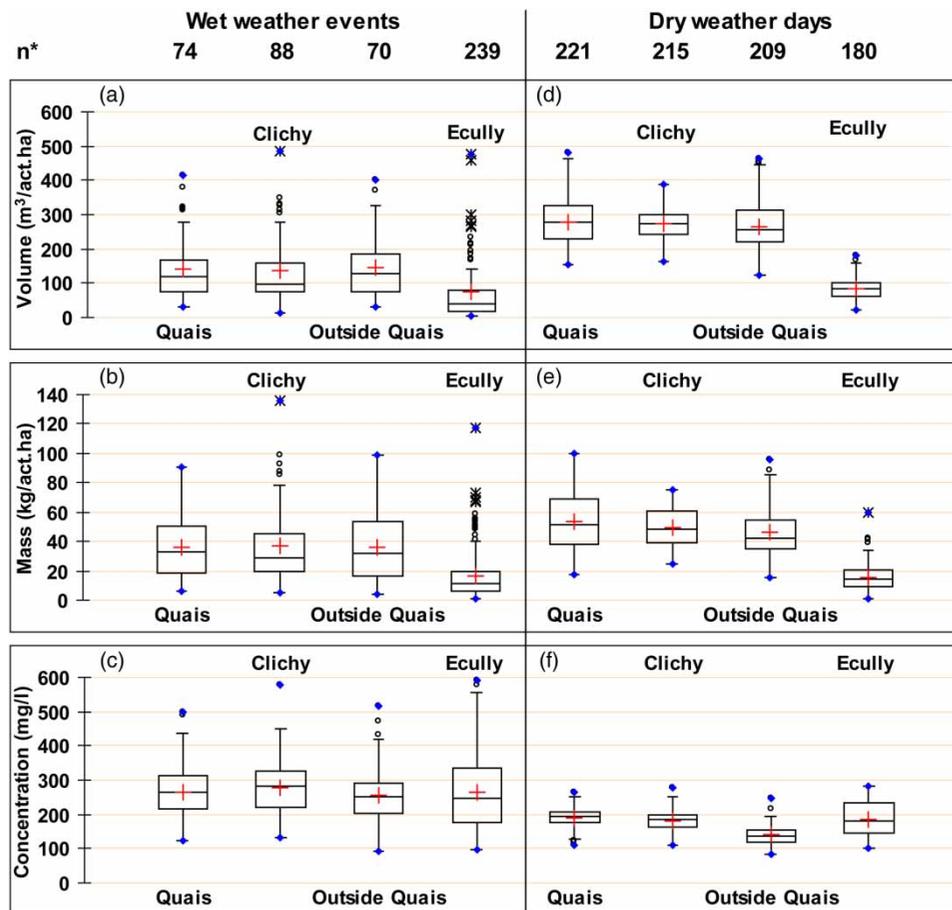

Figure 1 │ Volume, mass and event mean concentration (EMC) at the outlet of all the sites for rainfall events ((a), (b) and (c)) and dry weather days ((d), (e) and (f)). *n is the number of data.

graphical method allows the study of the distribution of a data set using its mean (cross mark), median (Q_2), lower (Q_1) and upper (Q_3) quartiles, and the extremes. Both the lower and upper whiskers define the so-called 'adjacent' values, which are determined from the inter-quartile deviation $IQ_r = Q_3 - Q_1$, and are greater or equal to $Q_1 - 1.5*IQ_r$ and less or equal to $Q_3 + 1.5*IQ_r$. Volumes and masses for each site are expressed in terms of active surface (active hectare = 'act.ha'). Note that the unit used with respect to time is 'per days' for dry weather and 'per event' for wet weather.

During wet periods on the Paris sites (Quais, Clichy and Outside Quais), the distributions of volume, mass and concentration are similar for Quais and Outside Quais, and, consequently, for Clichy (no significant differences between the sites are detected by the Friedman paired non-parametric test carried out at a 5% threshold). The mean specific values are around 140 m³/act.ha for event volumes (Figure 1(a)), 36 kg/act.ha for event masses (Figure 1(b)) and 270 mg/l for event mean concentration (EMC) (Figure 1(c)). The whiskers reveal some sharp variations in volumes, masses and EMC from one rainfall event to another. Indeed, the variations of the considered parameters, expressed as coefficient of variation (C_v), are greater than 60%. This variability during wet weather conditions is mainly due to the presence of extreme values especially for volumes and masses.

We obtained similar distributions between Paris sites for volumes (Figure 1(d)), masses (Figure 1(e), 'Paris sites') and concentrations (Figure 1(f), 'Paris sites') during dry weather conditions, but their variations are lower than those observed during wet weather conditions (C_v of all parameters during dry weather are less than 50%). The medians of TSS concentration during dry weather are lower than those observed during wet weather (Figure 1(f)), whereas the specific median of daily production (mass and volume) during dry weather days is two times higher than that of rainfall events (Figure 1(e) and (f)). Yet the 24-hour dry day production can hardly be compared with the rain event productions concentrating

over periods ranging from half an hour to 9 hours (first and last deciles of event duration distribution, see Table 2).

These results confirm those of Kafi *et al.* (2008) obtained from a small data set of rainfall events (between six and 16 rainfall events per site including less than five common rainfall events between sites) recorded on six embedded catchments in Paris (OPUR sites including our sites: Quais and Clichy) with similar land uses (Table 3). In fact, they observed no spatial variability of the wet weather pollutant masses (except for Quais site) and concentrations between the upstream and downstream of a large catchment (surface areas varies between 42 and 2,581 ha). The authors of this study attributed the difference in mass at Quais site compared to those of other sites to an overestimation of its active surface area. However, we did not observe such difference for 70 rainfall events. This difference may be due to the small number of rainfall events used in their study (Hannouche 2012).

The similar mean values (or median values) for both mass and volume productions observed for Paris sites, on the large data set of rainfall events, suggest that the source density of the two independent parts of the Clichy catchment is homogeneous, as might be expected from similar land uses (dense urban in our case). It would be interesting to find out the minimum spatial scale for which this coherence is observed and to search for the physical factors able to explain it.

In contrast with Paris sites, whatever the period (dry or wet), the productions (median values of volume and mass) of the Ecully residential catchment are twice lower than those observed on the Paris catchments. This can be accounted for by the difference in urbanization (production of wastewater volume per inhabitant (see Table 1), local practices in Paris (street cleaning), etc.). This has a small impact on concentrations: the mean and median concentrations at Ecully are similar to those found in Paris (Figure 1(f)), with no significant difference at a threshold of 5% (Mann–Whitney test). Furthermore, TSS concentrations, regarding combined sewers, in both dry and wet

Table 3 | Comparison between our results and those obtained by Kafi *et al.* (2008) for masses and concentrations (d_{10}–d_{90} (median))

	This study			Study of Kafi *et al.* (2008)		
Sites	Quais	Clichy	Outside Quais	Quais	Clichy	OPUR database (6 sites: 42 to 2,581 ha)
Mass (kg/act.ha)	12–69 (33)	10–76 (29)	11–67 (32)	11–31 (15)	24–60 (35)	11–61 (27)
Concentration (mg/l)	170–339 (267)	177–392 (281)	173–326 (254)	162–339 (233)	174–317 (250)	174–403 (279)

weather conditions, are in good agreement with the values found in the OPUR database (Gasperi *et al.* 2008; Kafi *et al.* 2008) or in the literature (Lee & Bang 2000; Suarez & Puertas 2005).

Correlations between sites for different rain events

The specific volume and mass and the EMC obtained for a common rainfall event selected among the 70 events available on both Quais and Clichy catchments are displayed in Figure 2. The correlation of mass, volume, and EMC between both sites is good with a determination coefficient above 0.8.

The runoff production on densely urbanized areas being closely correlated with rainfall, a high coefficient of correlation between the volumes is expected. This correlation implies a correlation between the event masses. Indeed, on these sites, the event volumes explain about 85% of the mass variation from one event to another (Hannouche 2012). The correlation between event masses and volumes is also observed on Ecully (Sun & Bertrand-Krajewski 2012) and on many other sites. Conversely, the high correlation coefficient between the concentrations is remarkable. We are currently verifying that this correlation between concentrations does not follow from the

correlations between both volumes and masses for the dispersion values displayed in Figure 2(c). Until now many attempts to find some significant correlations between concentrations and hydrologic or hydraulic parameters used for describing rain events have failed (Sun & Bertrand-Krajewski 2012). Yet, in the present case, we think that the correlation between the concentrations in both sites is a clue to some deterministic processes, which control concentrations specifically (i.e. with direct relationship with masses or volumes). Further investigations are needed to validate this assertion.

The correlations of volumes, masses and EMC of Quais and Outside Quais catchments are also significant (Figure 3), although the correlation coefficients are lower than those between Quais and Clichy catchments. These results confirm those discussed above and prove that the correlations between the Quais and Clichy catchments are not caused by the redundancy between the embedded catchments. Once again, the correlation between the concentrations is strikingly high ($R^2 = 0.74$, Figure 3(c)).

As a conclusion, we can say that the different values observed from one rainfall event to another may be induced by some processes, which re-occur on different catchments and appear to control either mass production or concentration.
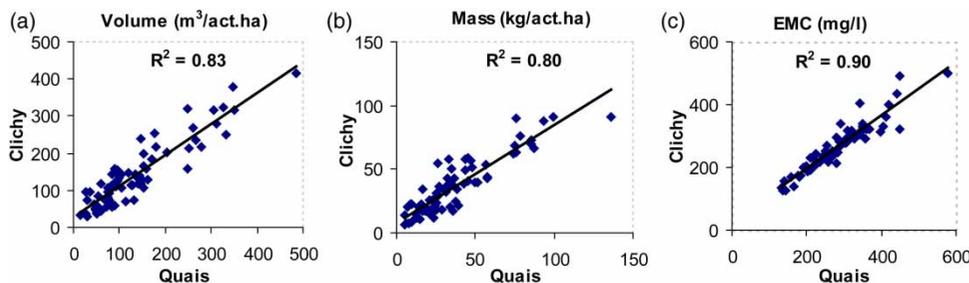

Figure 2 │ Inter-site comparison of volume (a), mass (b) and EMC (c) for events common to both sites.
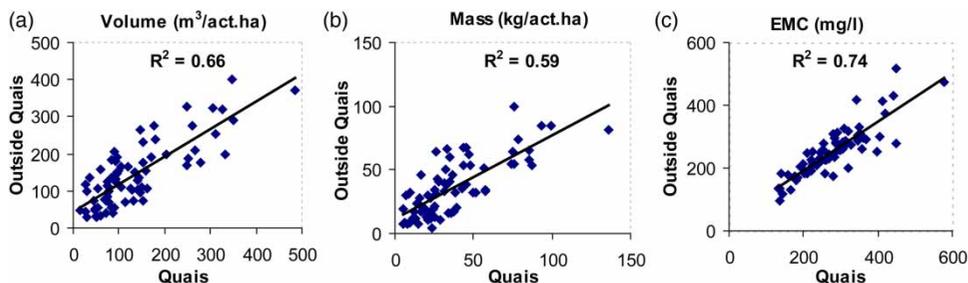

Figure 3 │ Comparison of volume (a), mass (b) and EMC (c) for events common to Quais and Outside Quais catchments.

Contribution of different sources to volume and mass results for each rain event

Distributions

The mass discharged at the outlet of a combined sewer system during a rain event (M_{Outlet}) has three distinct origins: the wastewater mass discharged during the event (M_{WW}), the surface runoff mass (M_{SR}) and the mass of deposits (M_{SD}) released from the sewer system.

In order to assess the respective contributions, the mass balance between the inlet and the outlet of the sewer network of each catchment area is carried out for each rain event ($M_{SD} = M_{Outlet} - M_{WW} - M_{SR}$). A detailed description of the calculation method is available in Hannouche *et al.* (in press). The absolute and relative contributions of each source to the water and suspended solids fluxes are presented in Table 4.

These contributions vary greatly from one rain event to another. However, high contributions of deposits are observed for all the three sites: sewer deposit contribution is more than 50% of the TSS event load on average, and more than 22% for 90% of rainfall events. Wastewater generates a significant fraction of the rainfall events' total volume (40 to 61% on average and d_{10} more than 16%) and total load (30 to 42% on average and d_{10} more than 7%) on all the three sites. By contrast, surface runoff is characterized by a small contribution to the TSS load (8 to 20% on average and d_{90} less than 37%) with a high

contribution to the rainfall events' total volume (more than 39% on average). For the range ($d_{10} - d_{90}$), we can see comparable absolute and relative values between Quais and Clichy sites which are slightly different from Ecully's relative contributions.

Except for surface runoff, Ecully's absolute contributions are lower than thos of Quais and Clichy's. The lower population density at Ecully site (see Table 1) may be one of the reasons for the lower values of wastewater and deposit absolute contributions than those obtained in Paris combined sewer system. Thus, wastewater smaller absolute contribution seems to induce smaller absolute contribution of deposits accumulated in combined sewers during dry weather periods. As regards runoff contributions, the production is controlled by the runoff concentration distribution, which has been selected for the assessment of this source (Hannouche *et al.* in press). Here, the different concentration distributions considered as inputs for the mass balance, described above, lead to the same mean production.

For the Paris sites, these results agree with those obtained during the OPUR program (Phase 2) on the same sites (Gasperi *et al.* 2010) (varies from 47 to 69%) and for two events (57 and 67%) obtained at Eindhoven, The Netherlands, by Schilperoort (2011). Moreover, the results show that the relative contribution of sewer deposits is substantial in a sewer system like the Ecully catchment. This site, indeed, with a slope of 2.7%, is considered as free of coarse sewer deposits contrary to Clichy's sewer network, whose site, with a slope of 0.14%, is heavily fouled.

Correlation between sites

Figure 4 presents the comparison between the absolute contributions (in kg/act.ha) of wastewater (WW), runoff (SR) and deposits (SD) to the TSS event loads of the Quais and Clichy sites for the same event.

The correlations are good for the contributions of the three sources between both sites, however somewhat lower than the correlations obtained for the total mass at the outlet (Figure 2(b)).

We do not compare here Quais and Outside Quais contributions because the many steps of the difference analysis (between sources and between catchment) generate excessive uncertainties (Hannouche *et al.* in press).

Again, we can conclude that some of the processes for mass production or concentration control are reproducible between catchments with similar land uses. These processes may be related to the mobilization of a variable part of the deposits, accumulated in dry periods, during rain events.

Table 4 | Absolute contributions (in m³/act.ha and kg/act.ha) and relative contributions (in % of each source to event volume and load transit at the outlet of each catchment)

	Source	Catchment	Mean	d_{10}	d_{90}
Wet weather volume	WW m³/act.ha (%)	Quais	66 (*55*)	32 (*37*)	122 (*73*)
		Clichy	78 (*61*)	29 (*42*)	137 (*79*)
		Ecully	22 (*40*)	5 (*16*)	50 (*72*)
	SR m³/act.ha (%)	Quais	61 (*45*)	16 (*27*)	163 (*63*)
		Clichy	62 (*39*)	10 (*21*)	160 (*58*)
		Ecully	56 (*60*)	3 (*28*)	123 (*84*)
Wet weather load	WW kg/act.ha (%)	Quais	13 (*37*)	4 (*21*)	19 (*47*)
		Clichy	12 (*42*)	4 (*26*)	20 (*65*)
		Ecully	5 (*30*)	2 (*7*)	14 (*57*)
	SR kg/act.ha (%)	Quais	4 (*11*)	1 (*5*)	9 (*22*)
		Clichy	4 (*8*)	1 (*4*)	8 (*15*)
		Ecully	4 (*20*)	1 (*6*)	10 (*37*)
	SD kg/act.ha (%)	Quais	19 (*52*)	5 (*37*)	41 (*67*)
		Clichy	18 (*50*)	4 (*27*)	40 (*64*)
		Ecully	9 (*50*)	4 (*22*)	19 (*79*)

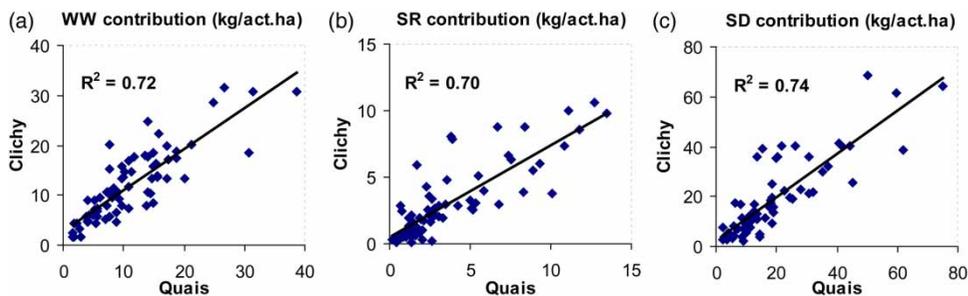WW: wastewater; SR: runoff; SD: deposits.

Figure 4 | Inter-site comparison of the different contributions to event load transit at the outlet of the catchments for the same rainfall events.

CONCLUSION

The large database presented in this study is a significant addition to the already available literature. In this paper, it is used to highlight some substantial variations in wet weather TSS fluxes from one rain event to another.

The results obtained for the spatial variations of TSS fluxes and concentrations and the values of the dry weather wastewater and deposit contributions satisfactorily agree with those obtained for other Paris sites with similar land uses.

Moreover, some additional results are used to highlight the following interesting findings.

- Masses and concentrations for different rain events are correlated between sites with similar land uses. The correlation between masses is a consequence of both the correlation between volumes (which is positive for densely urbanized catchments) and of the correlations between masses and volumes observed on many sites. The correlation between the concentrations is unexpected and may be a clue to some deterministic processes. However, more investigations need to be carried out to understand the phenomenon better.
- Regarding urban water discharges, wastewater seems to be a decisive factor for two reasons: First, wet weather wastewater generates straightforwardly a significant part of the total event load. Second, the deposits contribution, which is linked to dry weather wastewater deposited in combined sewers during dry weather periods, is also comparatively, although indirectly, substantial.
- The substantial contribution of sewer deposits is not specific to sewer systems like the Paris sewer network but concerns also other systems like, for instance, Ecully, a site with a steep slope and considered free of coarse sewer deposits.

The great diversity of behaviours is difficult to reproduce using classical global conceptual models. Instead, a somewhat more mechanistic and spatial distribution modelling approach is an innovative way that should be pursued. A method to investigate further the observed spatial coherence could consist of the detailed morphological analysis of the sewer collectors based on criteria related to the production and the transfer of particles in the sewer network.

ACKNOWLEDGMENTS

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