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 a number of 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 level of inter- and intra-events. On an inter-event scale, the present analysis deals with total volumes, masses and concentrations during both wet and dry weather periods, and includes the contributions of sources of different origin to event volume and TSS load values.
The results confirm previous findings regarding the spatial consistency of TSS fluxes and concentrations on sites in Paris with similar land uses. Moreover, masses and concentrations are correlated between the different sites and the correlation suggests that some deterministic processes are reproducible from one catchment to another for a particular rain event.
The results also demonstrate the importance of the contribution of dry weather wastewater and deposits to the total event loads and show that such contributions are not specific to Paris sewer networks.
Keywords: Combined sewer, spatial coherence, variability, sources, flux, concentration, turbidity, TSS.

INTRODUCTION

Many studies have been conducted over the last forty years to examine pollutant fluxes in urban wet-weather discharges (UWWD), (Saget, 1994; Suarez and Puertas, 2005; Gasperi *et al.*, 2012) determine their spatial and temporal variations and describe their entry into combined sewer systems (Lee and Bang, 2000; Kafi-Benyahia *et al.*, 2008). 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). Some also describe, though rather approximately, pollutants generation and transport processes (Ashley *et al.*, 1999). The results show that pollutant concentrations and fluxes both vary greatly during and between events.

Yet, (Kafi-Benyahia *et al.*, 2008) has observed some similar behaviours, as regards fluxes, concentrations of TSS and other parameters (COD, BOD_5, metals ...), between six catchments with similar land use and with catchment areas varying from *41 to 2581 ha*.

These results, however, have been obtained using a small set of rainfall event data recorded using conventional sampling methods. More recently, continuous turbidity measurements have allowed for the recording of time series, which are representative of suspended solids (principal carriers of contaminants) concentrations on different time scales (Lacour *et al.*, 2009; Hannouche *et al.*, 2011; Metadier and Bertrand-Krajewski, 2012).

The French observatories in urban hydrology *SOERE "URBIS"* are composed of *OPUR*-Paris, *OTHU*-Lyon and *ONEVU*-Nantes. 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, we call "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 serviced by a combined sewer system. The main characteristics of both catchments are displayed in *Table 1*. The Quais catchment is actually embedded into 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 part of the Clichy catchment which is complementary of "Quais" (called "Outside Quais"). Data processing, then, consists in 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).

Table 1: Main characteristics of the studied sites

Catchments	Quais	Clichy	Ecully
Surface area (ha)	402	942	245
Runoff coefficient (-)	0.64	0.68	0.15
Median slope (%)	0.14	0.10	2.7
Equivalent inhabitant BOD_5 (EH/active ha)	600	680	220
Average dry weather daily flow (l/EH/day)	450	400	380

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

Equipments and available data set

Both Paris sites are equipped with two redundant turbidity sensors (attenuation = 880nm, calibration using formazin and range = 0 - 2000 FAU), a conductivity sensor and a flow-rate sensor (CR2M 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 is derived from both available signals once their consistency had been verified. Turbidity, conductivity and flow-rate are recorded every 1 minute on both sites during all the 2006 rainfall events. 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 catchments (*Table 2*). Furthermore, we can identify 221 complete dry weather days for 'Quais' and 215 for "Clichy", including 209 days common to both sites.

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

	Rain depth (mm)	Mean intensity ($mm.h^{-1}$)	Max intensity ($mm.h^{-1}$)	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

On the "Ecully" site, flow, turbidity and conductivity data have been measured between 2004 and 2008. During this period, (Metadier and Bertrand-Krajewski, 2012) have 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; Metadier and Bertrand-Krajewski, 2012).

RESULTS AND DISCUSSION

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

Distributions

Volume (*V*), mass (*M*) and discharge weighted mean concentration (*C*) for both the rainfall events and the dry weather days are illustrated for all the studied catchments in *Figure 1* a Tukey box plots. This graphical method allows for 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).

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 m^3/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.

We obtain similar results for volumes (*Figure 1, d*), masses (*Figure 1, e*) and concentrations (*Figure 1, f*) of dry weather discharges, but the variations of the considered parameters are lower than the variations observed during wet weather days. The concentrations of dry weather discharges are lower than those observed during wet weather (*Figure 1, f*), whereas the average specific daily production (mass and volume) during dry weather days is twice as heavy as that of rainfall events (*Figure 1, e and f*). Yet the 24-hr dry day production can hardly be compared with the rain event productions concentrating over periods ranging from 2 hours to 12 hours (first and last deciles of event duration distribution).

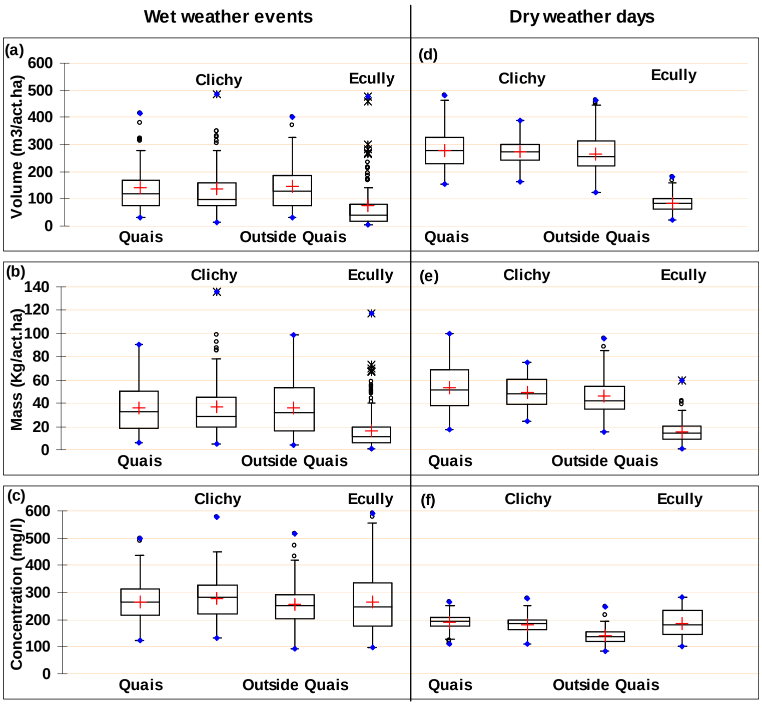

Figure 1: Volume, masse and event mean concentration at the outlet of all the sites for rainfall events (a, b and c) and dry weather days (d, e and f).

These results confirm those of (Kafi-Benyahia *et al.*, 2008) obtained from a small data set of rainfall events recorded on the same Paris sites. The similar mean values for both mass and volume productions suggest that the source density of the two independent parts of the Clichy catchment is homogeneous, as might be expected from similar land uses. 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, whatever the period (dry or wet), the productions (volume and mass) of the "Ecully" 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 weather conditions, are in good agreement with the values found in the Qastor database (Saget, 1994), in the OPUR database (Kafi-Benyahia *et al.*, 2008) or in the literature (Lee and Bang, 2000; Suarez and Puertas, 2005).

Correlations between sites for different rain events

The specific volume and mass and the EMC obtained for a same rainfall event selected among the 70 events available on both "Quais" and "Clichy" catchments are displayed in *Figure 2 (a, b, c)*. 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 (Joannis *et al.*, submitted). The correlation between event masses and volumes is also observed on “Ecully” (Sun and 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 and Bertrand-Krajewski, 2012). Yet, in the present case, we think that the correlation between the concentrations in both sites is a clue for some deterministic processes, which control concentrations specifically (i.e., with direct relationship with masses or volumes). Further investigations are needed to validate this assertion.

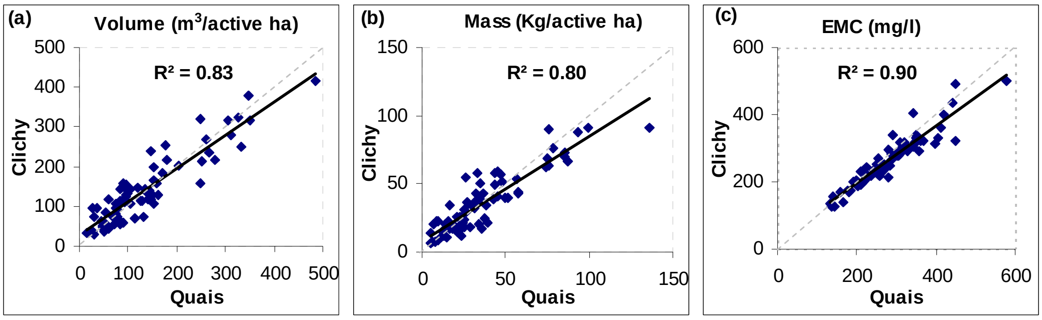

Figure 2: Inter-site comparison of volume (a), mass (b) and event mean concentration (c) for events common to both sites

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 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*).

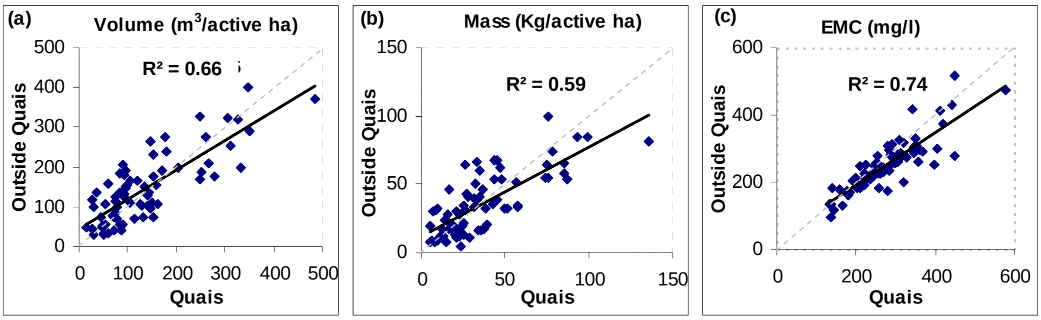

Figure 3: Comparison of volume (a), mass (b) and event mean concentration (c) for events common to “Quais” and “outside Quais” catchments.

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.

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, 2012). The absolute and relative contributions of each source to the water and suspended solids fluxes are presented in *Table 3*.

These contributions vary greatly from one rain event to another. However, the importance of the contribution of deposits for all the three sites can be considered as a permanent feature (more than 50% of the TSS event load on average). Wastewater generates a significant fraction of the rainfall event total volume (40% to 61% on average) and total load (30% to 42% on average) on all the three sites. Surface runoff, in comparison, is characterized by a small contribution to the TSS load (8% to 20% on average).

Except for surface runoff, "Ecully"'s absolute contributions are lower than "Quais"'s and "Clichy"'s. Wastewater and deposit contribution lower values may be explained by the lower population density. 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 distributions, which has been selected for the assessment of this source (Hannouche, 2012). Here, the different concentration distributions considered as inputs for the mass balance described above, lead to the same mean production.

Table 3: Absolute contributions (in m^3/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 m^3/act.ha (**%**)	Quais	66 (*55*)	32 (*37*)	122 (*73*)
		Clichy	78 (*61*)	29 (*42*)	137 (*79*)
		Ecully	22 (*40*)	5 (*16*)	50 (*72*)
	SR m^3/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*)

For the Paris sites, these results agree with those obtained during the OPUR program (Phase 2) on the same sites (Gasperi *et al.*, 2010). 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/ active 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*).

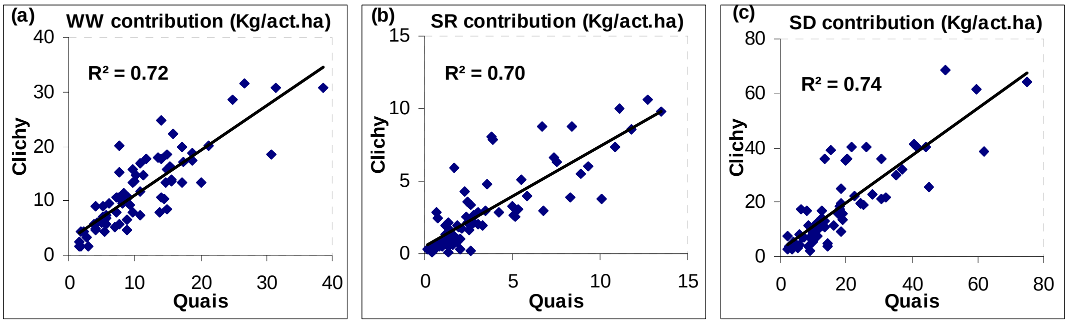

Figure 4: Inter-site comparison of the different contributions to event load transit at the outlet of the catchments for the same rainfall events

We have not, here, compared “Quais” and “Outside Quais” contributions because the many steps of the difference analysis (between sources and between catchment) generate excessive uncertainties.

Again, we can conclude that some of the processes for mass production or concentration control are reproducible between catchments. These processes may be related to the mobilization of a variable part of the deposits, accumulated in dry periods, during rain 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 for some deterministic processes. However, more investigations need to be carried out to understand the phenomenon better;

- Regarding urban water discharges, wastewater is 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, though 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, the some 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 in the detailed morphological analysis of the sewer collectors based on criteria related to the production and the transfer of particles in the sewer network.

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