Do storm event samples bias the comparison between sewer deposits contribution?

Mohamad Rammal, Ghassan Chebbo, José Vazquez and Claude Joannis

ABSTRACT

Previous researches demonstrated the occurrence of unique in-sewer sediment, the organic layer, on the Marais site in Paris, capable of explaining the entire wet weather sewer production of suspended particles. Other studies on sites having no similar organic sediment, Clichy in Paris and Ecully in Lyon, demonstrated a wet weather sewer deposits contribution (SDC) to effluent pollution comparable to that of the Marais site, casting therefore doubts on the implication of the organic layer to the outlet discharge pollution. So, an in-depth comparative investigation of the different sites' mean SDC was carried out to confirm or refute the major role of this layer vis-à-vis sewer production. The size and characteristics of the events' sample used to calculate the SDC were analyzed to find whether a statistical bias may have masked a difference that would be more coherent with field observations. After homogenizing these elements, the organic layer regained some of its previously alleged participation in sewer contribution (a maximum of 36% of the total SDC) but another unknown source was still dominant. This suggests that sewer sediment production during wet weather is a result of multiple sediment erosion: the organic layer and another major source not yet identified.

Key words | combined sewer, effluent pollution, events' characteristics, number of events, organic layer, sediment

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INTRODUCTION

In the last few decades, more scientific and operational interest has been raised on in-sewer sediments due to their substantial impact on pollution levels in combined sewer overflows (CSOs) (Ashley *et al.* 1994; Ashley & Verbanck 1996; Gromaire *et al.* 2001; Butler *et al.* 2003). This impact was evaluated on many combined sewers by a mass balance approach between inlet and outlet contaminant loads (Gromaire *et al.* 2001; Gasperi *et al.* 2010), highlighting therefore the necessity of improving our knowledge on sewer deposits (location, nature, and dynamics) for better management and control strategies of CSOs.

Therefore, many in-sewer investigations were conducted; among the most extensive was the one undertaken on the Marais urban catchment in Paris, for which the in-sewer deposits constitute a real issue, being drained by a combined sewer laid at very slack gradients (Gromaire *et al.* 1998). Among the three sewer deposits (sewer grits, organic layer, biofilms) identified on the Marais catchment, analysis of mass and chemical composition showed that

only the organic layer observed on the upstream parts of its main collectors can match the mass and characteristics of the eroded particles collected on the outlet (Ahyerre & Chebbo 2002), suggesting that the organic layer constitutes the major source of particles during wet weather periods.

However, other studies made on other sewers question the validity of this result. Further investigations of the Paris sewer (e.g. Clichy catchment) (Kafi-Benyahia 2006) did not show a similar organic sediment layer in its collectors, even in places favorable for deposition, while having comparable sewer contribution to that of the Marais. Similar findings were also obtained on the Ecully catchment in Lyon, having very different sewer characteristics (steep invert slope) (Métadier 2011), where no single trace of organic layer was detected in its main collectors although its sewer demonstrated an important contribution to the pollution of outlet discharges (Hannouche *et al.* 2014). These findings imply that another source other than the organic layer is being eroded on these sewers. Since this source

should also exist in the Marais sewer, which has more favorable conditions for sedimentation, the contribution of the organic layer becomes doubtful.

This incoherence between previous findings could be due to one of two reasons: (1) a bias induced by some elements or hypotheses made in the mass balance calculation, which are different between the studied sites, or (2) the in-sewer deposit detected only on the Marais catchment is not the real source of wet weather suspended solids production as believed so far. Since only the former reason can be investigated, we identified all possible aspects composing it and that are susceptible to inducing a bias in the calculation method to examine them:

1. the measurement techniques employed to acquire the quantity and quality data used in these studies with their associated uncertainties;
2. the calculation method of the mass balance equation used to calculate the sewer deposits contribution (SDC) with its associated hypotheses;
3. the size and the characteristics of the rainfall events' samples taken for this analysis.

Concerning the first point, in the measurement campaigns made on the previously mentioned sewers, particular attention was paid to the precision and robustness of the procedures adopted for data acquisition, and thus results are considered quite reliable (Gromaire 1998; Métadier 2011). Concerning the hypotheses made in the calculation procedure (temporal extrapolation of wastewater total suspended solids (TSS) load from dry weather to wet weather and spatial extrapolation of runoff TSS load from gauged areas to ungauged areas), they were previously studied by Gromaire (1998) and Hannouche (2012) who ended up with the same conclusion, i.e. the effect of these hypotheses is minor on the SDC evaluation. However, the number of events being considered and their characteristics were found to be different from one site to another and may induce a bias in the contribution evaluations. So, the objective of this article is to find out whether one of these two elements used in the mass balance

calculations could have masked an important difference between the different sites' contribution and thus was misleading in the comparison made between sites and the conclusion drawn on the principal sewer source. For this aim, a homogenization of these elements was performed before comparing again the sewer deposits' contribution. The study is organized in the following way: the first part presents the studied sites and the database used; the second one discusses the calculation of each term in the mass balance equation and the results obtained previously. Then, in the third and fourth part, the homogenization of the characteristics and number of events, and a comparison of the corresponding results are made. Finally, a conclusion on the effect of the studied elements on the contribution comparison is presented.

MATERIALS AND METHODS

Studied sites

The three urban catchments studied in this article were the subject of recent researches conducted within two French observatories: OPUR, which studied the Paris sites (Marais and Clichy, the first being totally embedded in the second) (Gromaire 1998; Hannouche 2012), and OTHU, which studied the Lyon site (Ecully) (Métadier 2011). The surface and sewer characteristics are summarized in Table 1. The three sites are residential and drained by a combined sewer system. However, they differ in terms of surface area and the percentage impervious area along with the sewer characteristics. Unlike Parisian sites, Ecully has a highly dense sewer system (only main channels considered) with an important slope that explains the absence of fine organic sediments in its sewer. On the Clichy site (outside its Marais upstream part), sewer examinations in places having probably suitable flow conditions for deposition were carried out with an endoscope device that permitted observation of in-sewer sediments without disturbing them. They did not show any trace of organic sediments (Kafi-Benyahia 2006).

Table 1 | Surface and sewer characteristics of the studied catchments

Site	Surface, S (ha)	Population density	Percentage of impervious area	Sewer type	Total length of main channels, L (m)	L/S (m/ha)	Slope of main channels (%) (d10 – mean – d90)
Marais	41	287 EHN/ha[a]	91	Combined	1,824	44	0.001–0.06–0.71
Clichy	942	373 EHN/ha	85	Combined	19,222	20	0.002–0.10–0.30
Ecully	245	33 EH/ha	42	Combined	16,851	69	1–2.70–6

[a]EHN: equivalent inhabitant of total Kjeldahl nitrogen.

On the Marais site, a considerable quantity of both coarse and the overlying organic deposits was found at the upstream parts, with the depth of the former varying between 2 and 45 cm and that of the latter between 2 and 15 cm. A comparison between the characteristics of these deposits and those observed at the sewer outlet during rainfall events showed that the organic layer is the only potential source of eroded particles (Ahyerre & Chebbo 2002). The erodible fine portion of the coarse deposits ($<400\ \mu m$) showed a particulate volatile content (volatile matter/TSS) of 13–17–22% (d_{10}–d_{50}–d_{90}), whereas the organic layer has a strictly higher organic composition (60–68–75%). So, in comparison to the eroded particles' organic content (58–67–76%) in addition to other pollutants' contents (chemical oxygen demand, biochemical oxygen demand, Cd, Cu, Pb, Zn), it is evident that the organic layer is the most probable sediment type generating these particles. For more details, the reader is referred to Ahyerre (1999) and Garnaud (1999).

Used database

The entire database used in this study was taken from measurements realized in two observatories: OPUR in Paris and OTHU in Lyon (Gromaire 1998; Métadier 2011; Hannouche 2012).

Rainfall events

Table 2 summarizes the characteristics of the rainfall events identified on each of the three sites, based on the precipitation data collected using rain gauges with tipping buckets installed on each site. On Paris sites, the events are longer and more intense than those on the Ecully site, especially on the Marais site, whereas the variability of dry weather periods does not seem to be different between the three sites.

Flow rate data

The database of the flow rate at the outlet of the three sites was constructed on the basis of continuous measurements made by a flowmeter during dry and wet weather periods. On the Marais and Ecully sites, flow rate measurements were recorded at a 2 minute time step, whereas on Clichy a 1 minute time step was fixed for these measurements.

TSS concentration data

This study exploited the TSS concentration data acquired by various measurement techniques: point and continuous, and, for the latter, attenuation and nephelometric turbidity measurements. On the Marais site, automatic sampling was carried out at the outlet of the sewer system at time steps of constant flow volume (number of samples varying between three and 23 samples), where samples were then analyzed to measure the TSS concentration during both dry and wet weather periods. On Clichy and Ecully sites, continuous turbidity measurements made at their outlets were validated by Lacour (2009) and Métadier & Bertrand-Krajewski (2011a) respectively. Then, the conversion of turbidity values into TSS concentration was made using TSS–turbidity relationships determined on similar sites (Cordon Bleu and Saint-Mihiel in Nantes) for Clichy (Hannouche *et al.* 2014) and using a site-specific relationship for Ecully (Bertrand-Krajewski *et al.* 2008; Métadier & Bertrand-Krajewski 2011b). The mean and variability of the event mean concentration (EMC) determined on wet weather and dry weather periods on the three sites are represented in Table 3. Distributions of TSS concentration of wet weather were found to be statistically similar for the three sites. For wet weather events, the Mann–Whitney–Wilcoxon test was always positive (p-value >0.05) when applied to each

Table 2 │ Characteristics of the rainfall events on the three studied sites

Site	Monitoring period	Number of events	Statistic	H (mm)	I_m (mm/h)	I_{max} (mm/h)	D (hr:min)	ADWP (days)
Marais	From 15/05/1996 to 10/10/1997	30	Min	2.6	1.1	2.5	00:06	0.03
			d_{50}	7.1	3.5	21.8	02:06	1.30
			Max	21.6	35.3	192	07:15	29.90
Clichy	From 1/12/2015 to 31/12/2006	88	Min	1.0	0.3	1.2	00:10	0.10
			d_{50}	4.5	1.8	9.15	01:40	1.41
			Max	23.8	66.7	240	13:10	23.20
Ecully	From 2004 to 2008	160	Min	0.16	0.13	0.34	00:05	0.17
			d_{50}	3.00	0.93	6.105	00:26	1.17
			Max	69.95	29.14	118.67	49:26	23.56

H, precipitation depth; I_m, average rainfall intensity on event duration; I_{max}, maximum intensity on 1 minute; D, rainfall event duration; ADWP, antecedent dry weather period.

Table 3 │ Order of magnitude of the minimum (min), mean and maximum (max) of the event mean concentration on the three studied sites

	Outlet event mean concentration (mg/L)					
	Wet weather events			Dry weather days		
	Min	Mean	Max	Min	Mean	Max
Marais	121	221	519	97	154	208
Clichy	130	280	580	103	184	285
Ecully	97	270	596	100	188	290

two-site combination (Marais–Clichy: $p = 0.19$, Marais–Ecully: $p = 0.91$, Clichy–Ecully: $p = 0.48$). This indicates that the TSS mass on the studied sites normalized by the flow volume (which is proportional to the catchment surface, precipitation depth and population density) is similar between the three sites.

As far as surface runoff is concerned (water flow on all urban surfaces before entering the sewer network), the data of TSS concentration found in literature were used. But since Paris presents a particular case in terms of street cleansing practices (street sweeping occurs so frequently: 5 days/week), data acquired on catchments representative of the Parisian context (Gromaire *et al.* 1999) were used for both the Marais and Clichy site. Measurements of surface runoff concentration were made for each surface type (roads, roofs, and courtyards) and thus were considered distinctly when calculating the EMC of TSS from runoff flow:

- For the roads' EMC, values vary between 41 mg/L and 413 mg/L with a mean of 126 mg/L.
- For courtyards' EMC, values vary between 5 mg/L and 665 mg/L with a mean of 101 mg/L.
- For rooftops' EMC, values vary between 5 mg/L and 121 mg/L with a mean of 25 mg/L.

For Ecully, since land and local practices are significantly different from those of Paris catchments, values measured on comparable residential sites (EPA 2005) were used instead where a lognormal distribution of runoff TSS concentration was selected (with a mean of 100 mg/L and a standard deviation of 176 mg/L).

Calculating contribution of different sources to pollutants' load

SDC to pollutants' load for each rainfall event on the three sites was derived from a mass balance equation applied between the inlet and the outlet of the sewer network.

$$M_{SD} = M_{Outlet} - M_{RS} - M_{WW} \tag{1}$$

$M_{Outlet} =$ total TSS mass measured at the outlet of the sewer system during rainfall event

$M_{RS} =$ TSS mass at the sewer outlet coming from surface runoff flow

$M_{WW} =$ TSS mass at the sewer outlet coming from wastewater

$M_{SD} =$ TSS mass at the sewer outlet coming from exchange with sewer deposits

M_{Outlet}: M_{Outlet} was calculated by the product of the water volume conveyed to the sewer outlet during the rainfall event (V_{Outlet}) and the TSS concentration measured at the same point (C_{Outlet}). On the Marais site, the total volume was multiplied by the EMC, whereas on Ecully and Clichy the continuous measurements made permitted a direct integration of the product of the instantaneous flow rate and the instantaneous TSS concentration.

M_{RS}: On the Marais site, M_{RS} was obtained by the product of the total runoff volume V_{RS} flowing during the rainfall event and the TSS EMC of runoff C_{RS}. Since TSS concentration of the three typical Paris surface types (roofs, roads, and courtyards) was measured (Gromaire 1998), a distinction between these surfaces was made when calculating the surface contribution. On Clichy, the same method was applied to calculate the surface runoff contribution while using the runoff volume calculated on Clichy and the runoff concentration of different surface types measured on the Marais. On Ecully, since the land uses are different from those of Paris sites, the transposition of concentration measurements to this site was not reasonable and thus the whole watershed was treated as one entity. So, the runoff volume (V_{RS}) that was calculated by the difference between the total volume measured at the outlet and the estimated volume of wastewater was then multiplied by a concentration taken from the literature (EPA 2005) for similar catchment areas.

M_{WW}: A hypothesis was made for the three sites that the wastewater flow and the particles associated during the rainfall event are identical to those that would have been transited during dry weather condition. For Clichy, M_{WW} was determined using a statistical model developed by Hannouche (2012) based on the continuous measurements of flow rate and turbidity acquired on Clichy in dry weather conditions. For Ecully site, M_{WW} was determined by the method presented by Métadier & Bertrand-Krajewski (2011a), which is based on searching the dry weather days

that best fit the turbidity and flow rate signals before and after the rainfall event where uncertainty measurements were taken into consideration. On the Marais site, this value was deduced by multiplying the wastewater volume that flowed during this event by the dry weather wastewater concentration measured at the outlet.

A comparison was first made on the statistical distribution of the percentage event's SDC. Then, the comparison criterion adopted in this study for further analysis is a comparative determinand that characterizes the site contribution on an overall scale. It is evaluated by the weighted mean contribution on the whole set of available events (of size N) denoted here by α_N:

$$\alpha_N = \frac{\sum_{i=1}^{N} M_{SDi}}{\sum_{i=1}^{N} M_{Outlet i}} = \frac{\sum_{i=1}^{N} P_i M_{Outlet i}}{\sum_{i=1}^{N} M_{Outlet i}} \tag{2}$$

where P_i is the percentage contribution of each event

Homogenizing the mass balance between the different sites

Homogenizing the events' set characteristics

The rainfall events taken on the three sites were compared with each other to find out if they share the same characteristics or not. The comparison was made according to the distribution of their different characteristics (precipitation depth (H); average rainfall intensity on event duration (I_m); maximum intensity on 1 minute (I_{max}); rainfall event duration (D); antecedent dry weather period (ADWP)). The non-parametric Mann–Whitney–Wilcoxon test was employed to compare the distribution of these characteristics. It showed that the storm events studied cannot be considered as drawn from the same distributions. *P*-values obtained show that the characteristics of rainfall events on the three sites are not homogeneous except for the rainfall depth on Ecully and Clichy and the antecedent dry weather period on Marais and Clichy (Table 4).

For that reason, we sorted all the rainfall events on the three sites and selected those having their characteristics within the same interval for each of their major characteristics (H, I_m, I_{max}, D, and ADWP). This interval was fixed by reference to the smallest sample, namely the one from the Marais site, with two extreme events being excluded.

Homogenizing the events' sample size

To evaluate the effect of this element on the weighted mean SDC α_N, we took the same number of events on paired sites, taking the minimum number of available events for each pair. On Clichy, many selections of 30 events can be performed in order to compare Clichy and Marais sites on the basis of α_{30s}. Similarly on Ecully, many α_{30s} and α_{88s} values can be derived for comparison with Marais and Clichy sites respectively. So, we carried out a sufficiently big number of simulations (10^6 iterations) to account for most of the possible combinations of these events to calculate a distribution of α_N. Then, we calculated the mean $\overline{\alpha_N}$ of all these iterations and the 10th and 90th percentile to compare the interval $[d_{10}, d_{90}]$ with the α_N value calculated on the site with the lower number of available events.

RESULTS AND DISCUSSION

SDC on the whole rainfall event set

First, the results of SDC on the studied sites are represented in Figure 1(a) as a distribution of the percentage event's SDC using boxplots. The boxplot used herein represents the median of the data by a central line mark inside a box whose edges are the 25th and 75th percentiles, with their corresponding whiskers extending to the $d_{25}-1.5$ $(d_{75}-d_{25})$ and $d_{75}+1.5$ $(d_{75}-d_{25})$ values respectively. Finally, all data points falling outside this interval are considered to be outliers that, when existing, are plotted individually outside the whiskers using a plus mark (+). Sewer deposits are shown to be the main contributor to suspended solids in urban wet weather discharges on the three sites, where we obtained a mean value (the cross mark (×)

Table 4 | Results of the *p*-values obtained by Mann–Whitney statistical test on the comparison of rainfall events' characteristics distribution

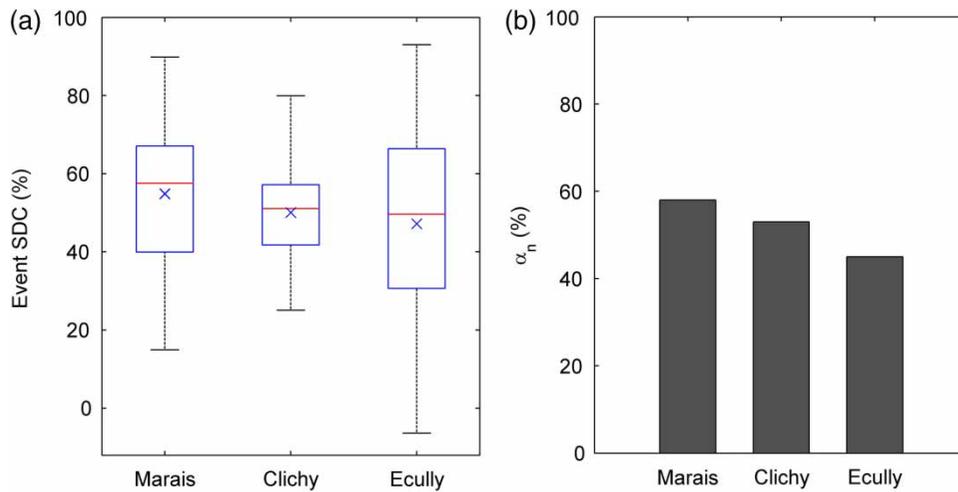| P-value (Mann–Whitney)	H		I_m		I_{max}		D		ADWP	
	Clichy	Ecully	Clichy	Ecully	Clichy	Ecully	Clichy	Ecully	Clichy	Ecully
Marais	1.37×10^{-5}	5.78×10^{-6}	0.0013	2.67×10^{-9}	0.0067	1.73×10^{-5}	0.0028	0.021	0.245	0.0027
Clichy	–	0.744	–	1.59×10^{-9}	–	0.0427	–	5.3×10^{-6}	–	0.0013

Figure 1 │ (a) Statistical distribution of the percentage event SDC for the three studied sites, (b) mean SDC α_N on the three sites.

inside the box) of 55%, 50%, and 47% on Marais, Clichy, and Ecully respectively. Then, the comparison is made with respect to α_N.

Results of weighted mean SDC α_N (Figure 1(b)) revealed more difference between Ecully (45%) and the other sites (58% on the Marais and 53% on Clichy) than the previous comparison. The difference of α_N between Marais and Ecully and between Clichy and Ecully with respect to Ecully's α_N (30% and 18% respectively) might be logically referred to the organic layer. Since this sediment layer was only found on the Marais sewer and thus on a small part of Clichy sewer, it is quite consistent to have larger difference between Marais and Ecully than between Marais and Clichy.

These small differences show that the organic layer cannot be the major sewer source of suspended particles production during wet weather on the Marais catchment. They suppose that another source must exist on the Marais as well as on the other two sites and that is being eroded during wet weather. This is especially true regarding the high contribution of sewer deposits on Ecully where no organic layer is found (SDC = 45%). This source could be some organic particles accumulating along the main collectors not necessarily having very mild slope and very low flow velocity. Their accumulation occurs in a very thin, hardly observable layer but which could constitute a considerable mass of TSS when eroded on the sewer scale. This source could alternatively be a sewer stock accumulated on the very upstream sewer lines that are not well investigated due to their hard accessibility. These lines receive very low input flows and thus present very suitable conditions for organic deposits accumulation, especially when these are freshly entering the sewer before being subjected to any kind of decomposition and thus settle more easily.

However, in the light of the different elements used in calculating SDC, particularly the storm events' number and characteristics, the small differences obtained between sites might be only a result of these factors hiding a larger difference that fits more with field observations and results about the major role of the organic layer.

Effect of events' set characteristics on SDC

The homogenization procedure of the events' set characteristics yielded 28 events on the Marais site, 45 events on the Ecully site, and 49 events on the Clichy site, whose characteristics are represented in Table 5.

These events showed similar distributions using Mann–Whitney test for all its characteristics. The distribution of the event SDC between the three sites and the weighted mean SDC α_N were determined on these selected events and are displayed in Figure 2(a) and 2(b) respectively. The new comparison results dispelled completely the difference between the three sites' contributions, tipping the scales towards the nil involvement of the identified organic layer on the Marais to its wet weather sewer production.

But before confirming that, two points seem to be important to examine: whether the compared sets are sufficiently comparable to cancel the effect of events' characteristics and whether the characteristics taken really influence SDC or not. The former could be due to the methodology applied to select similar events between sites or the characteristics used in this selection, and the latter could be due to the classical characteristics taken that are not representative of the in-sewer processes.

Table 5 | Characteristics of the selected rainfall events on the three sites

Site		H (mm)	I_m (mm/h)	I_{max} (mm/h)	D (hr:min)	ADWP (days)
Marais (28 events)	Minimum	2.6	1.1	2.5	00:06	0.03
	Median	7.45	3.55	21.20	02:09	1.085
	Maximum	21.6	35.3	144	07:15	29.90
Clichy (49 events)	Minimum	2.4	1	2.3	00:10	0.4
	Median	5	1.7	13.30	02:43	1.7
	Maximum	19.6	26	144	13:10	23.20
Ecully (45 events)	Minimum	2.4	0.93	3.6	00:09	0.21
	Median	4.8	2.117	12	02:35	1.45
	Maximum	22.96	29.14	118.67	15:20	11.67
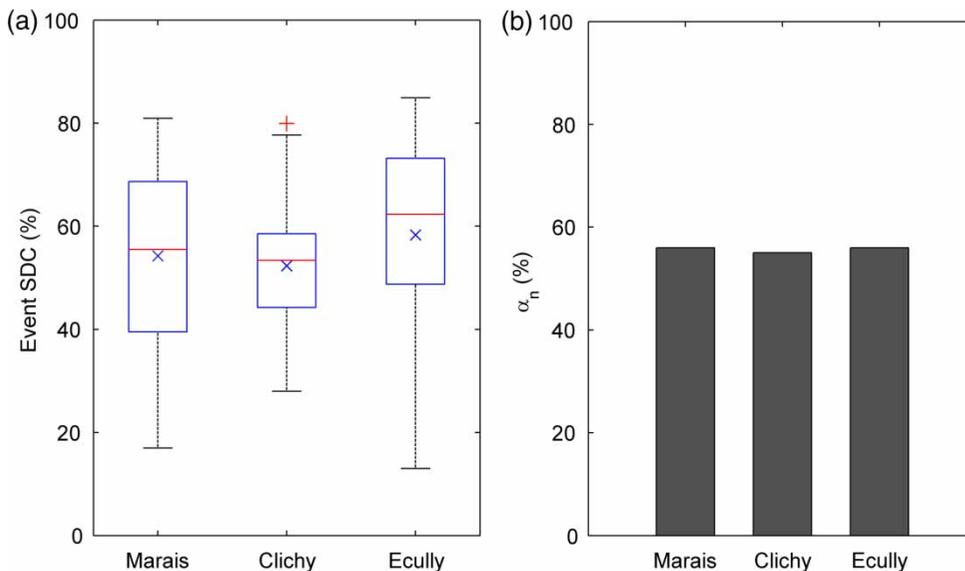
Figure 2 | (a) Statistical distribution of the percentage event SDC for the three studied sites on the new selected rainfall events, (b) mean SDC α_N for the new set of rainfall events on the three sites.

We decided first to level up our sieving criteria of the rainfall events by comparing the contribution event by event, each taken from a different site with almost identical characteristics. We identified 14 rainfall events that are very similar for Marais and Clichy, and six that are identical for Marais and Ecully. The characteristics of these events are represented in Figures 3 and 4 respectively. In five out of six events, the contribution on Ecully to effluents' pollution was found to be more than that on the Marais. Between Marais and Clichy, seven out of the 14 selected events showed higher contribution to effluents' pollution on Clichy than the Marais. These results suggest that the organic layer does not significantly contribute to effluent pollution.

Before confirming this point, we assessed the relevance of these characteristics to the studied quantity by calculating the correlation between the percentage events SDC on each site with the events' characteristics. No identifiable impact of these characteristics was recorded for any site where none of the events' characteristic yielded a good correlation with the SDC (max R^2 obtained was 0.36). The reason may be that these parameters are not representative of the effective flow energy driving sediment production inside the sewer system, but rather of the processes taking place on the surface. Parameters that could reflect the events' potential of mass production are those that characterize the actual hydraulic conditions inside the sewer section especially in places where erodible deposits are found. However, these parameters are not available and require specific measurement techniques or modeling approaches to be acquired.
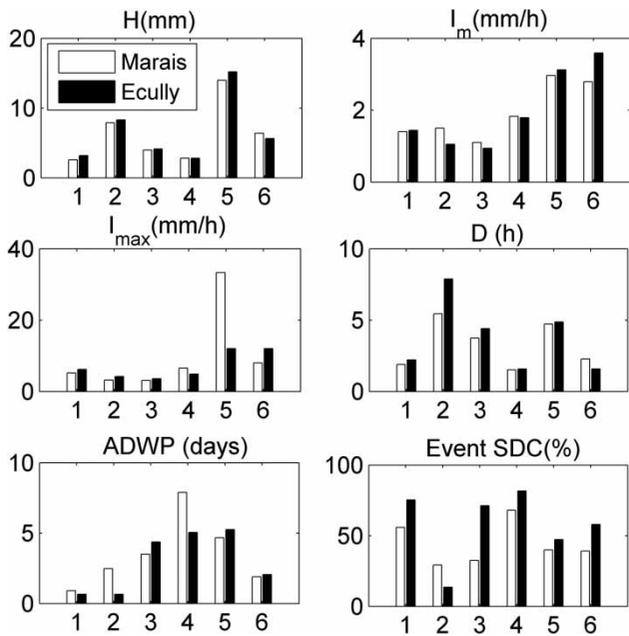
Figure 3 | Comparison of SDC and characteristics of selected rainfall events on Marais and Ecully.

Effect of events' set size on SDC

The results of SDC on the three sites after implementing the previously explained method of events' set size homogenization are illustrated in Figure 5.

The variability obtained on α_N for Ecully when reduced to 30 events (especially the lower boundary of the interval) shows that the mean SDC on the Marais can hardly exceed that of Ecully by more than 21%. This percentage that can be transposed to the Marais site, as both sites have similar normalized TSS load (Table 3), represents only 36% of the total SDC on the Marais (21% out of the 58%), which could be reasonably explained by the sediment source identified on the Marais. At the same time, this confirms the existence of another source on the Marais similar to that of Ecully that might be contributing 64–93% of the Marais whole contribution. These percentages are calculated by proportioning respectively the lower and upper boundary of the interval of SDC obtained on Ecully to the total SDC on the Marais (37/58 and 54/58). Results on Clichy were less expressive where both contributions
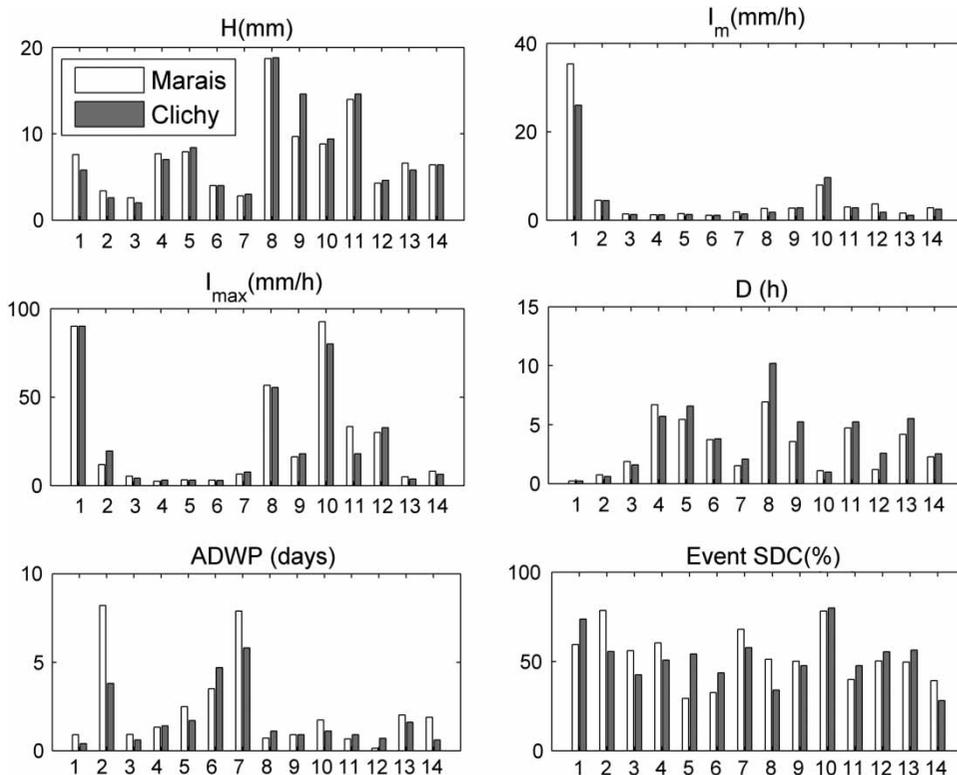

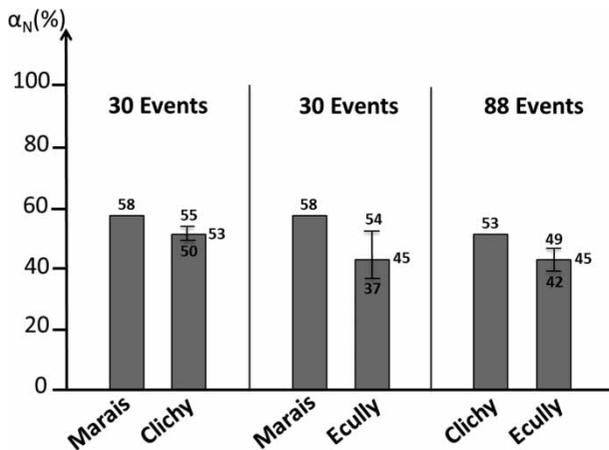**Figure 4** | Comparison of SDC and characteristics of selected rainfall events on Marais and Clichy.

Figure 5 │ Comparison between the mean SDC α_N obtained on each site for the same number of events, with 10th and 90th percentiles of α_n distributions.

on the Marais and Clichy remained close with a maximum absolute difference of 8%. This could be explained by the probable occurrence of the organic layer on the Clichy site sharing the same characteristics as the Marais but that have not yet been identified during sewer visits. This is confirmed by the difference obtained between Clichy and Ecully when both are considered for 88 events. These two sites, which are supposed to have very similar SDC as both have no organic layer, showed a difference that mounts up to 20% between their SDC (obtained by the relative difference between α_{88} on Clichy and the lower boundary of α_{88} on Ecully with respect to the former $= (53 - 42/53) \times 100$). This difference is explained by the fact that the Marais site where organic layer was detected is embedded in Clichy and is thus contributing to the SDC on Clichy.

CONCLUSIONS

In this study, a comparative analysis is carried out between different urban catchments having comparable SDC but different fouling state to address the paradox between SDC calculations and field observations. *In situ* studies conducted on the Marais urban catchment suggest that the organic layer detected in its collectors can explain the whole or most of its wet weather sewer production. However, the comparison of the SDC of this catchment with others having no similar sediment source (Clichy and Ecully) deprives this potential source from its alleged production involvement as all catchments present comparable SDC.

In order to settle the contradiction between these outcomes, an analysis is carried out on their reliability where a couple of uncertainty sources had been identified and are likely to provide helpful elements when played down: events' set number and events' characteristics used to calculate the SDC. First, for the events' characteristics, two different homogenizations were tested, one by the global distribution parameters and the other by events' parameters. Neither method unveiled the expected difference between the compared sites' contribution. Second, the homogenization of the number of events between the different sites highlighted two principal points:

- *The first point concerns the involvement of organic layer in sewer production.* The difference obtained between the site having organic layer (Marais) and the other having no trace of these organic sediments (Ecully) cannot be totally explained by sampling procedure since, with all the homogenizations made, no single case gave identical contributions. This confirms that the organic layer does contribute to sewer production during wet weather but by a moderate percentage (<36% of the SDC on the Marais).
- *The second point concerns the apportionment of SDC to different sewer deposits.* Results revealed that the major percentage (>64% of SDC on the Marais) can still not be attributed to the organic layer, in contradiction to previous studies (Ahyerre & Chebbo 2002), since the difference between sites' SDC did not increased sufficiently for the contribution of the organic layer (deduced from the difference of SDC between site having organic layer and another having no organic layer) to outweigh that of the unknown source (deduced from the contribution of sites having no organic layer).

So, in terms of the solids production sources in sewer systems, results suggest that the principal source is not the organic layer observed in the upstream section of primary sewer facilities during field surveys, although it still contributes to solid production. Some hypotheses are supposed for the principal source. It could be either distributed randomly along the sewer system due to local decay of hydraulic capacity or located in the upstream secondary sewer where dry weather flow conditions might favor particle sedimentation. These hypotheses should be later verified by field visits and observations during dry and wet weather or by a modeling approach using an elaborate distributed model that distinguishes the differently behaving parts of the drainage system.

REFERENCES

Ahyerre, M. 1999 *Bilans et mécanismes de migration de la pollution organique en réseau d'assainissement unitaire (Balance and mechanism of the migration of organic pollution in combined sewer system)*. PhD thesis, Université Paris VI, Paris, France.

Ahyerre, M. & Chebbo, G. 2002 Identification of in-sewer sources of organic solids contributing to combined sewer overflows. *Environmental Technology* **23** (9), 1063–1073. DOI:10.1080/09593332308618353.

Ashley, R. M. & Verbanck, M. 1996 Mechanics of sewer sediment erosion and transport. *Journal of Hydraulic Research* **34** (6), 753–770. DOI:10.1080/00221689609498448.

Ashley, R. M., Arthur, S., Coghlan, B. P. & McGregor, I. 1994 Fluid sediment in combined sewers. *Water Science and Technology* **29** (1–2), 113–123.

Bertrand-Krajewski, J. L., Barraud, S., Kouyi, G. L., Torres, A. & Lepot, M. 2008 On-line monitoring of particulate pollutant loads in urban sewer systems: stakes, methods, example of application. *La Houille Blanche* **4**, 49–57.

Butler, D., May, R. & Ackers, J. 2003 Self-cleansing sewer design based on sediment transport principles. *Journal of Hydraulic Engineering* **129** (4), 276–282. DOI:10.1061/(ASCE)0733-9429(2003)129:4(276).

EPA 2005 *Alex Maestre and Robert Pitt: The National Stormwater Quality Database, Version 1.1. A Compilation and Analysis of NPDES, Stormwater Monitoring Information*. Department of Civil and Environmental Engineering, The University of Alabama, Tuscaloosa.

Garnaud, S. 1999 *Transfert et évolution géochimique de la pollution métallique en bassin versant urbain (Transfer and geochemical evolution of metallic pollution in urban catchments)*. PhD thesis, Ecole des Ponts ParisTech, Champs-sur-Marne, France.

Gasperi, J., Gromaire, M.-C., Kafi, M., Moilleron, R. & Chebbo, G. 2010 Contributions of wastewater, runoff and sewer deposit erosion to wet weather pollutant loads in combined sewer systems. *Water Research* **44** (20), 5875–5886. DOI:10.1016/j.watres.2010.07.008.

Gromaire, M. C. 1998 *La pollution des eaux pluviales urbaines en réseau d'assainissement unitaire. Caractéristiques et origins (The pollution of urban stormwater in a combined sewer system: Characteristics and origins)*. PhD thesis, Ecole Nationale des Ponts et Chaussées, Champs-sur-Marne, France.

Gromaire, M. C., Chebbo, G. & Saad, M. 1998 Origins and characteristics of urban wet weather pollution in combined sewer systems: the experimental urban catchment 'Le Marais' in Paris. *Water Science and Technology* **37** (1), 35–43. DOI:10.1016/S0273-1223(97)00753-1.

Gromaire, M.-C., Garnaud, S., Gonzalez, A. & Chebbo, G. 1999 Characterisation of urban runoff pollution in Paris. *Water Science and Technology* **39** (2), 1–8. DOI:10.1016/S0273-1223(99)00002-5.

Gromaire, M.-C., Garnaud, S., Saad, M. & Chebbo, G. 2001 Contribution of different sources to the pollution of wet weather flows in combined sewers. *Water Research* **35** (2), 521–533. DOI:10.1016/S0043-1354(00)00261-X.

Hannouche, A. 2012 *Analyse du transport solide en réseau d'assainissement unitaire par temps de pluie: exploitation de données acquises par les observatoires Français en hydrologie urbaine (Analysis of solid transport in combined sewer network during wet weather: exploitation of data acquired by the French observatories in urban hydrology)*. PhD thesis, Université Paris-Est, Champs-sur-Marne, France.

Hannouche, A., Chebbo, G. & Joannis, C. 2014 Assessment of the contribution of sewer deposits to suspended solids loads in combined sewer systems during rain event. *Environmental Science and Pollution Research* **21** (8), 5311–5317. DOI:10.1007/s11356-013-2395-1.

Kafi-Benyahia, M. 2006 *Variabilité spatiale des caractéristiques et des origines des polluants de temps de pluie dans le réseau d'assainissement unitaire parisien (Spatial variability of characteristics and origins of pollutants of wet weather flow in Paris combined sewer system)*. PhD thesis, Universite Paris-Est, Champs-sur-Marne, France.

Lacour, C. 2009 *Apport de la mesure en continu pour la gestion de la qualité des effluents de temps de pluie en réseau d'assainissement (Contribution of continuous turbidity measurements to the management of effluent quality in sewer systems during wet weather)*. PhD thesis, Universite Paris-Est, Champs-sur-Marne, France.

Métadier, M. 2011 *Traitement et analyse de séries chronologiques continues de turbidité´ pour la formulation et le test de modèles des rejets urbains par temps de pluie (Treatment and analysis of continuous turbidity series for the test of urban stormwater quality models)*. PhD thesis, National Institution of Applied Sciences in Lyon, Lyon, France.

Métadier, M. & Bertrand-Krajewski, J. L. 2011a Assessing dry weather flow contribution in TSS and COD storm events loads in combined sewer systems. *Water Science and Technology* **63** (12), 2983–2991.

Métadier, M. & Bertrand-Krajewski, J. L. 2011b From mess to mass: a methodology for calculating storm event pollutant loads with their uncertainties, from continuous raw data time series. *Water Science and Technology* **63**, 369–376. DOI:10.2166/wst.2011.230.