

# PRIORITY POLLUTANTS IN URBAN STORMWATER: PART 2 - CASE OF COMBINED SEWERS

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## Abstract

This study has evaluated the quality of combined sewer overflows (CSO) in an urban watershed, such as Paris, by providing accurate data on the occurrence of priority pollutants (PPs) and additional substances, as well as on the significance of their concentrations in comparison with wastewater and stormwater. Of the 88 substances monitored, 49 PPs were detected, with most of these also being frequently encountered in wastewater and stormwater, thus confirming their ubiquity in urban settings. For the majority of organic substances, concentrations range between 0.01 and 1  $\mu\text{g.l}^{-1}$ , while metals tend to display concentrations above 10  $\mu\text{g.l}^{-1}$ . Despite this ubiquity, CSO, wastewater and stormwater feature a number of differences in both their concentration ranges and pollutant patterns. For most hydrophobic organic pollutants and some particulate-bound metals, CSOs exhibit higher concentrations than those found in stormwater and wastewater, due to the contribution of in-sewer deposit erosion. For pesticides and Zn, CSOs have shown concentrations close to those of stormwater, suggesting runoff as the major contributor, while wastewater appears to be the main source of volatile organic compounds. Surprisingly, similar concentration ranges have been found for DEHP and tributyltin compounds in CSOs, wastewater and stormwater. The last section of this article identifies substances for which CSO discharges might constitute a major risk of exceeding Environmental Quality Standards in receiving waters and moreover indicates a significant risk for PAHs, tributyltin compounds and chloroalkanes. The data generated during this survey can subsequently be used to identify PPs of potential significance that merit further investigation.

## Keywords

Combined sewer overflows, priority pollutants, urban area, stormwater, Water Framework Directive.

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## 1 **1. Introduction**

2           The European Community's strategy for combating surface water pollution by means  
3 of a control policy was set forth in the European Water Framework Directive 2000/60/EC  
4 (WFD). Decision no. 2455/2001/EC, adopted by the European Parliament and Council on  
5 November 20, 2001, established the list of priority substances in the field of water policy and  
6 amended Directive 2000/60/EC. This decision provided the first list of 33 substances or  
7 groups of substances to be identified as action priorities at the Community level. Among these  
8 priority pollutants (PPs), some have been identified as "priority hazardous substances", whose  
9 emissions, discharges and losses are scheduled to be phased out or completely removed. More  
10 recently, on July 17, 2006, the Commission adopted a Directive intended to set mandatory  
11 environmental quality standards on priority substances, requiring Member States to come into  
12 compliance by 2015 in order to ensure a "satisfactory chemical status for surface water".

13           In pursuit of these WFD objectives through identifying possible pollutant reduction  
14 measures, an inventory of sources in the urban environment has definitely proven necessary.  
15 Since priority pollutants can enter aquatic ecosystems via effluents from wastewater treatment  
16 plants and industries, as well as via combined sewer overflows (CSOs) and stormwater,  
17 accurate knowledge of the PPs discharged by such sources is required. Even though a number  
18 of studies or National Action Plans have been undertaken to identify the occurrence and  
19 significance of specific PPs in wastewater (Rule *et al.*, 2006a, b; Rowsell *et al.*, 2010;  
20 Eriksson *et al.*, 2010), in wastewater treatment plant effluent (Ruel *et al.*, 2010) and in the  
21 aquatic system (Gasperi *et al.*, 2009), no comprehensive broad overview of the PP  
22 contamination of stormwater in both separate and combined sewers is available. The  
23 continued existence of uncontrolled or poorly-controlled discharges from stormwater and  
24 CSOs could however constitute a major reason for the long-term persistence of low-quality  
25 water (Clark *et al.*, 2006). Moreover, the magnitude of stormwater pollutant loads, their

1 subsequent acute impact on receiving waters and their reliable and sensitive modelling have  
2 all remained key issues since 1990 (Chebbo and Saget, 1995; Deletic, 1998; Suarez and  
3 Puertas, 2005; Lau *et al.*, 2009; Dotto *et al.*, 2010). Although Eriksson *et al.* (2007) proposed  
4 a list of substances based on a theoretical assessment of stormwater substances (CHIAT:  
5 Chemical Hazard Identification and Assessment Tool), this list has not yet been  
6 experimentally screened on stormwater samples. To date, only limited information is  
7 available on a number of historical substances such as metals, polycyclic aromatic compounds  
8 (PAHs) and polychlorinated biphenyls (PCBs) (Iannuzzi *et al.*, 1997; Gromaire *et al.*, 2001;  
9 Davis *et al.*, 2001; Rossi *et al.*, 2004).

10 Due to this lack of information available on PP levels in urban stormwater in both  
11 separate and combined sewers, the OPUR research programme (Observatory of Urban  
12 Pollutants, 2006-2012) has sought to investigate stormwater quality in urban watersheds. The  
13 general objective herein has been to provide data on both the occurrence and concentration of  
14 PPs along with a few additional substances in stormwater and CSOs. A methodology based  
15 on the EU's list of priority substances and the CHIAT approach was therefore developed by  
16 Zgheib *et al.* (2008) in conjunction with a list of 88 pollutants (containing 80 organic  
17 substances and 8 metals) and ultimately adopted in order to monitor stormwater quality. In  
18 considering that the analyses carried out on unfiltered samples yield poor-quality data with  
19 respect to the representativeness of sample contamination in addition to offering only partial  
20 information on the chemical fate, the applicable methodology requires analysing both the  
21 dissolved and particulate fractions. The first step of the OPUR programme was dedicated to  
22 stormwater quality in connection with the urbanisation gradient (from residential to more  
23 densely urbanised areas, **Figure 1**). This work is partially described in Zgheib *et al.* (2011a)  
24 and then more extensively discussed in Zgheib *et al.* (2011b, same issue). In accordance with  
25 the same methodology and approach, the present study, as the second part in a two-article

1 series, focuses on CSO quality. The largest CSO outfall in the Paris metropolitan area was  
2 equipped and a total of 4 CSO discharges were considered. Since CSOs make up a mixture of  
3 untreated wastewater and stormwater, the wastewater quality was also investigated according  
4 to the same methodology (i.e. through monitoring of the 88 pollutants identified). This study  
5 therefore is the first relevant assessment to provide new and accurate knowledge on the  
6 occurrence and concentrations of a wide array of pollutants in CSOs and on their significance  
7 in comparison with concentrations found in wastewater and stormwater. The final objective of  
8 this paper is to determine the potential impact of CSO discharges in receiving waters, as  
9 regards Environmental Quality Standards (EQS).

## 10 **2. Materials and methods**

### 11 *2.1 Site description and rain event characteristics*

12 Paris proper (*intra-muros*) is drained by a combined sewer system covering a land area  
13 of 105 km<sup>2</sup>. This area is densely populated (2.15 million inhabitants, i.e., approximately  
14 20,500 inhabitants/km<sup>2</sup>) and features many small shops, offices and very little industrial  
15 activity. In this study, the largest CSO outfall, located in Paris' north-western district, has  
16 been considered ("Clichy" outfall, [Figure 1](#)). Over the 2009-2010 period, some 52 discharges  
17 occurred annually, responsible for discharging between 25,000 and 1,000,000 m<sup>3</sup> into the  
18 Seine River. This outfall is supervised by the Paris public sanitation service (SIAAP).

19 In order to collect CSO samples, flow was continuously monitored using an automatic  
20 flowmeter that combined water level and velocity sensors; moreover, water samples were  
21 collected by two automatic vacuometric samplers equipped with glass and plastic bottles for  
22 organic and inorganic sampling, respectively. Teflon pipes were also used. Samples were  
23 removed at a fixed time interval (about 5 min), and 6 sub-samples per bottle were collected.  
24 The bottles were then picked up in order to produce a flow-weighted composite sample

1 representative of the entire rain event as determined by flow rate measurements. A total of 4  
2 CSO discharges were thus collected. Table 1 summarises the main characteristics of the rain  
3 events and discharges (precipitation height, volume discharged, conductivity, etc.). Two  
4 exceptional discharges, corresponding to summer storms, were collected on July 12<sup>th</sup> and  
5 14<sup>th</sup>, 2010 (**C1 and C2 event designation**), with volumes of roughly 600,000 and 1,000,000  
6 m<sup>3</sup>, respectively. Moderate discharges (September 8<sup>th</sup> and 24<sup>th</sup>, 2010) were also collected (**C3  
7 and C4 event designation**). This type of discharge has been the most frequently observed at  
8 the Clichy outfall over the last 2 years, during which time a discharge range from 40,000 to  
9 300,000 m<sup>3</sup> has encompassed about 80% of all discharges. At the same site, wastewater was  
10 also collected and analysed. **According to the conductivity of raw sewage (between 1,050-  
11 1,170  $\mu\text{S}\cdot\text{cm}^{-1}$  measured on the site during dry periods) and values provided by Kafi *et*  
12 *al.* (2008) for runoff (80 - 150  $\mu\text{S}\cdot\text{cm}^{-1}$ ), the runoff and wastewater proportions can be  
13 calculated with a simple linear regression using the conductivity of the flow-weighted  
14 composite sample since conductivity is conservative. To consider uncertainties in the  
15 method calculation, the minimal and maximal runoff proportions were calculated  
16 (hypothesis min: 1,050 and 150  $\mu\text{S}\cdot\text{cm}^{-1}$  for runoff and wastewater, hypothesis max:  
17 1,170 and 80  $\mu\text{S}\cdot\text{cm}^{-1}$ , respectively).**

18 For the studied discharges, the proportion of runoff remains especially high (at least  
19 69%-75% of runoff). The discharges on July 14<sup>th</sup> (C2) exhibited the highest runoff  
20 proportion, while the September 8<sup>th</sup> (C3) value was noteworthy for its slightly lower runoff  
21 proportion (Table 1). Other discharges (**C1 and C4**) revealed runoff proportions of between  
22 75% and 89%. Similar estimations based on nitrogen concentration provided comparable  
23 results.

## 1 **2.2 Experimental procedure**

### 2 *Routine wastewater parameters*

3 For each sample, routine wastewater parameters, such as total solids (TS), chemical  
4 and biochemical oxygen demands (COD and BOD<sub>5</sub>), ammonium (NH<sub>4</sub><sup>+</sup>), total Kjeldahl  
5 nitrogen (TKN), total phosphorous (P<sub>tot</sub>) and orthophosphates (PO<sub>4</sub><sup>3-</sup>), were analysed. As  
6 reported in Supporting Table 1, these parameters were measured in accordance with French  
7 standards.

### 8 *Priority substances*

9 As described by Zgheib et al. (2011b, same issue), a total of 88 substances were  
10 monitored for each sample (Table 2). Except for metals and volatile organic compounds  
11 (VOCs) including halogenated volatile organic compounds and BTEX (benzene\* (in **this**  
12 **article, priority hazardous substances are marked with \***), toluene, ethylbenzene and  
13 xylenes) which were analysed on the total fraction, both dissolved and particulate fractions  
14 were assessed for each individual compound. Analysis was performed by the IPL-Brittany  
15 Laboratory, certified by the French Ministry of Ecology, Sustainable Development, Transport  
16 and Housing (via the COFRAC accreditation committee).

## 17 **3. Results and discussion**

### 18 *3.1 Wastewater quality parameters in combined sewer overflows*

19 Routine wastewater quality parameters for the collected discharges as well as for a  
20 large number of rain events (SIAAP CSO database, n=52) are given in Table 3. Data for  
21 wastewater (on the same site) and runoff (Kafi *et al.*, 2008) are also reported. In spite of a  
22 high runoff proportion, the CSO reveals an organic strength (COD concentrations greater than  
23 140 mg.l<sup>-1</sup>, BOD<sub>5</sub> above 40 mg.l<sup>-1</sup>), albeit with less household wastewater than is typical  
24 (Tchobanoglous *et al.*, 2003). While C1 and C4 discharges were quite similar in their

1 concentrations of carbonaceous pollution, differences were still observed between C2 (the  
2 lowest concentration) and C4 (the highest). These differences may be partially tied to: i) the  
3 relative proportion of wastewater that gets mixed with runoff, and ii) the previous dry period  
4 prior to these rain events. A rougher comparison of CSO and wastewater concentrations  
5 allows differentiating two groups of parameters. The first group, which includes BOD<sub>5</sub>, TKN  
6 and NH<sub>4</sub><sup>+</sup>, exhibits higher wastewater concentrations than the group observed during the  
7 storm period, thus underscoring the fact that wastewater constitutes the major source for these  
8 pollutants. In the literature, it is well documented that most of these elements originate mainly  
9 from human sources (especially via urine and faeces) and from various activities such as  
10 washing and cooking (Wilkie *et al.*, 1996; Tchobanoglous *et al.*, 2003). More recently,  
11 Gasperi *et al.* (2010) confirmed that wastewater is the major source of organic and  
12 nitrogenous pollution in CSOs. The second group comprised COD, TS and P<sub>tot</sub>, with these  
13 parameters presenting comparable wastewater and CSO concentrations. While urban runoff  
14 contains rather low COD, TS and P<sub>tot</sub> concentrations, wastewater dilution by runoff should  
15 induce even lower CSO concentrations. This trend however was not observed, owing to the  
16 erosion of in-sewer deposits accumulated during dry weather flow periods in sewer trunks  
17 (Gromaire *et al.*, 2001). At the scale of Paris' combined sewer, Gasperi *et al.* (2010) indicated  
18 that from 47% to 69% for TS and from 34% to 61% for COD are tied to the erosion of in-  
19 sewer deposits; on the other hand, runoff only plays a minor role.

### 20 **3.2 Priority pollutants in combined sewer overflows**

#### 21 *Priority pollutants and detection frequency*

22 Depending on the rain event under consideration (C1, C2, C3 and C4), between 34 and  
23 44 PPs were detected. While the number of detected PPs ranges between 34 and 38 for C1,  
24 C2 and C3, C4 with the highest wastewater proportion exhibited the greatest number of  
25 detected PPs (n=44). On the whole, 39 PPs were never detected in CSOs. In comparison, 33

1 and 25 PPs were never quantified in stormwater (Zgheib *et al.*, 2011, same issue) and  
2 wastewater (Zgheib *et al.*, 2010), respectively. Out of these 39 never detected PPs and by  
3 comparing all matrices (CSO, wastewater and runoff), 30 substances were either never  
4 detected or only detected with a frequency of less than 15% (Table 4). The full list of  
5 undetected molecules, as well as their detection and quantification limits, is provided in  
6 Supporting Table 2. The non-quantification of most molecules may be explained by the levels  
7 of these chemicals lying below the available analytical limits of detection (as is typically the  
8 case for low-level metals such as Cd\* or Pt, PCB 194, or octa-BDE). For other substances,  
9 their non-quantification is indicative of being phased out in France and removed from the  
10 market (which is the case for several banned pesticides, hexachlorobenzene\* or carbon  
11 tetrachloride). Of the 88 priority substances monitored in both the particulate and dissolved  
12 phases, 49 different PPs including 19 priority hazardous substances\* (PHS\*) were detected  
13 (Table 4).

#### 14 *Priority pollutant concentrations and comparison with levels found in wastewater and* 15 *stormwater*

16 To better visualise the PP contamination of CSOs, the total even mean concentrations  
17 (expressed in  $\mu\text{g.l}^{-1}$ ) for the discharges considered have been reported in Figure 4. The  
18 concentrations of 58 PPs (i.e. 88 PPs monitored minus 30 PPs never detected) are illustrated.  
19 Additional information on dissolved and particulate concentrations is provided in Supporting  
20 Table 3. In comparing the quality of CSO with that of other matrices, the concentrations  
21 found for stormwater (n=15, Zgheib *et al.*, 2011 - same issue) and for wastewater have also  
22 been given in Figure 4. For both matrices, the median concentrations (d50) as well as the first  
23 and last deciles (d10 and d90) are listed. For wastewater, since no significant differences in  
24 wastewater contamination were observed between Clichy (n=7) and other experimental sites  
25 (n=4), all data on wastewater quality were compiled (n=11). For each matrix and compound,

1 the frequency of detection (%) is also indicated. Moreover, Figure 4 illustrates the ratios  
2 between CSO concentrations and the median wastewater or runoff concentrations.

### 3 *Metals*

4 High concentrations of Zn (658-1,137  $\mu\text{g.l}^{-1}$ ), Cu (86-134  $\mu\text{g.l}^{-1}$ ) and Pb\* (46-175  $\mu\text{g.l}^{-1}$ )  
5 were observed in CSOs. Cr was also noticeable yet at lower concentrations (12-20  $\mu\text{g.l}^{-1}$ ),  
6 in accordance with the low levels reported in domestic wastewater (Comber and Gunn, 1996).  
7 From an overall perspective, the metal concentrations found were close to those reported by  
8 Gromaire *et al.* (2002) in wet weather flows at the scale of the Marais catchment (centre of  
9 Paris, 4<sup>th</sup> arrondissement): 1,024-3,343  $\mu\text{g.l}^{-1}$  for Zn, 132-377  $\mu\text{g.l}^{-1}$  for Pb\*, and 58-208  $\mu\text{g.l}^{-1}$   
10 for Cu. These results resembled those found by Kafi *et al.* (2008) at the largest Paris city scale  
11 (760-1,832  $\mu\text{g.l}^{-1}$  for Zn, 55-289  $\mu\text{g.l}^{-1}$  for Pb\* and 66-231  $\mu\text{g.l}^{-1}$  for Cu).

12 As illustrated in Figures 1 and 2, CSO exhibits higher Cu and Pb\* concentrations and  
13 a much higher Zn concentration than those of wastewater. As initially reported by Gromaire  
14 *et al.* (2001), and depending on the metal under consideration, these differences may be  
15 explained by: i) the high metal concentrations found in runoff, or ii) in-sewer deposit erosion.  
16 As regards Cu and according to the authors, runoff and wastewater are only minor  
17 contributors (less than 30%), while exchanges with in-sewer stocks remain a considerable  
18 source (30%-70%). For Zn and Pb\*, runoff serves as the main source of CSO pollution at the  
19 scale of the Paris sewer network. This strong contribution from runoff is highly correlated  
20 with the heavy metal contamination of roof runoff. Gromaire *et al.* (2002) demonstrated that  
21 such heavy metal contamination is mainly correlated with Paris' roofs since most of them  
22 feature metal roof coverings and fittings.

23 As for Zn and Pb\*, CSOs also exhibit higher concentrations than those measured in  
24 stormwater by Zgheib *et al.* (2011b, same issue). The difference observed is mainly explained  
25 by the change in land use between suburban catchments and the Paris metropolitan area.

1 While the suburban catchments considered by Zgheib et al. (2011b, same issue) to  
2 characterise stormwater are residential (most buildings equipped with tile roofs), the majority  
3 of roofs within the Paris city limits have been fitted with metal materials, such as lead fittings  
4 and zinc sheets, thus leading to high metal concentrations.

#### 5 *Polycyclic Aromatic Hydrocarbons (PAHs)*

6 In this study, all 16 US-EPA PAHs were monitored: naphthalene\* (N), acenaphthalene  
7 (Acen), acenaphthylene (Acyl), fluorene (F), phenanthrene (P), anthracene\* (A\*),  
8 fluoranthene\* (Fluo\*), pyrene (Pyr), benzo[*a*]anthracene (B(a)A), chrysene (Chry),  
9 benzo[*a*]pyrene\* (B(a)P\*), benzo[*b*]fluoranthene\* (B(b)F\*), benzo[*k*]fluoranthene\* (B(k)F\*),  
10 dibenz[*ah*]anthracene (D(ah)A), benzo[*ghi*]perylene\* (B(ghi)P\*), and indeno[*cd*]pyrene \*  
11 (IP\*). The CSO concentrations of  $\Sigma$  16 PAHs ranged from 0.98 to 2.58  $\mu\text{g.l}^{-1}$ . Concentrations  
12 found in CSOs were typically within the same range as those reported by Kafi *et al.* (2008)  
13 (1.04-4.81  $\mu\text{g.l}^{-1}$  for  $\Sigma$  16 PAHs, with the median equalling 2.12  $\mu\text{g.l}^{-1}$ ). No special  
14 relationship between PAH concentrations and the proportion of runoff was observed. PAHs  
15 were correlated with TS since they are preferentially associated with particulate matter (>  
16 85% for  $\Sigma$  16 PAHs). PAHs with light molecular weights (LMW, 2 or 3 benzene rings) were  
17 predominant in dissolved phase, while PAHs with high molecular weights (HMW, 4 to 6  
18 benzene rings) were predominant in particulate phase. For  $\Sigma$  16 PAHs, HMW contributes to  
19 more than 75% of total PAHs. As suggested by this predominance and the high contributions  
20 of fluoranthene\* and pyrene (approx. 15% each), the PAH distribution confirms the pyrolytic  
21 origins of this contamination (Soclo *et al.*, 2000). This contamination can certainly be  
22 correlated with the high density of combustion sources inside Paris city limits. The Paris  
23 metropolitan area indeed generates heavy road traffic; consequently, both diesel- and  
24 gasoline-powered vehicles are responsible for emitting great quantities of PAH into the  
25 environment.

1 In sum, CSO concentrations appear to be higher than those measured in wastewater  
2 and stormwater at suburban catchment outlets (spanning the range from residential to  
3 densely-populated urbanised areas). Stormwater concentrations actually varied between 0.77  
4 and 6.14  $\mu\text{g.l}^{-1}$  (with the median at 1.36  $\mu\text{g.l}^{-1}$ ), while the concentrations found in wastewater  
5 occupied the 0.20-1.22  $\mu\text{g.l}^{-1}$  range (median: 0.47  $\mu\text{g.l}^{-1}$ ). As previously explained for Cu and  
6 organic matter, the erosion of in-sewer deposits can explain the differences observed.  
7 According to Gasperi *et al.* (2010), who established the mass balance of PAH loads during  
8 wet weather flows, the wastewater and runoff contributions do not exceed 30%, while in-  
9 sewer processes constitute a major source of PAHs (between 40% and 70%).

#### 10 *Polychlorinated biphenyls (PCBs)*

11 Despite being banned in France since 1987, six congeners (PCB 28, 101, 118, 138,  
12 153 and 180) were commonly detected in CSOs with total concentrations ranging from 12 to  
13 26  $\text{ng.l}^{-1}$  (Fig. 1). These concentrations found in CSOs were lower than those reported by  
14 Rossi *et al.* (2004) in stormwater (0.11-403  $\text{ng.l}^{-1}$ ). The authors however have reported similar  
15 PCB distributions dominated by heavy congeners (PCB 138, 153 and 180), thus reflecting  
16 typically diffuse inputs (Chevreuil *et al.*, 1996).

17 As for PAHs, rainy periods enhance PCB wastewater concentrations (Figs. 1 and 2).  
18 During dry periods, low PCB levels have been measured in wastewater (2.0-12.0  $\text{ng.l}^{-1}$ , with  
19 the median at 4.2  $\text{ng.l}^{-1}$ ), which shows good agreement with the values reported by Vogelsang  
20 *et al.* (2006) (3.4-4.1  $\text{ng.l}^{-1}$ ). Since CSO concentrations are higher than concentrations found  
21 in bulk deposition for Paris (0.6 and 8.1  $\text{ng.l}^{-1}$  for  $\Sigma$  7 PCBs, according to Blanchard *et al.*,  
22 2007), the difference in PCB concentrations during dry and wet periods can most certainly be  
23 explained by the remobilisation of PCB stock either on the urban surfaces or within the  
24 combined sewer. The difference in PCB distributions between bulk deposition and CSO, as  
25 characterised by a more pronounced contribution of heavy congeners (PCB 138, 153 and

1 180), has confirmed these local inputs. Surprisingly, CSO concentrations are far less than the  
2 values reported for stormwater by Zgheib et al. (2011b, same issue), i.e. 74, 272 and 711 ng.l<sup>-1</sup>  
3 for d10, d50 and d90, respectively, based on  $\Sigma$  7 PCBs. These differences may be due to  
4 either a higher probability of finding PCB stock in suburban catchments or the higher  
5 remobilisation of PCB stock on these catchments. Further investigation is now required to  
6 better understand these differences.

### 7 *Tributyltin compounds*

8 The concentrations of tributyltin\* (TBT\*), dibutyltin\* (DBT\*) and monobutyl\*  
9 (MBT\*) compounds are all illustrated in Figure 4. Whereas C1, C2 and C4 discharges exhibit  
10 similar concentration ranges (29-32 ng.l<sup>-1</sup> for TBT\*, 30-47 ng.l<sup>-1</sup> for DBT\* and 47-64 ng.l<sup>-1</sup>  
11 for MBT\*), discharge C3, which features a higher wastewater proportion, revealed 2-10 times  
12 higher concentrations (105, 220 and 750 ng.l<sup>-1</sup> for TBT\*, DBT\* and MBT\*, respectively).  
13 These concentrations were explained by a higher TS concentration, along with an increase of  
14 the organotin contents in these particles. As an example, for MBT\*, a distinct content  
15 difference was observed (0.75  $\mu\text{g.g}^{-1}.\text{dw}$  vs. 0.18-0.35  $\mu\text{g.g}^{-1}.\text{dw}$ ). In CSOs, the distributions  
16 were clearly marked by the predominance of MBT\* (38%-68%), followed by DBT\* (19%-  
17 38%). Up until this point however, the occurrences of MBT\* and DBT\* have primarily been  
18 correlated with the microbial and/or photochemical degradation of TBT\*, as the presence of  
19 both compounds and their lack of dependence on TBT\* provide support to the notion that  
20 DBT\* and MBT\* occur not only as degradation products of TBT\*.

21 Except for discharge C3, which clearly exhibits higher concentrations than those  
22 reported in either stormwater (Zgheib *et al.*, 2011, same issue) or wastewater, no notable  
23 difference in concentration ranges appears for TBT\*, DBT\* and MBT\* in CSO, wastewater  
24 and stormwater (Figs. 1 and 2). These similar concentration ranges observed across all  
25 matrices are certainly derived from the frequency of organotin occurrence and its wide

1 industrial applications (pesticides used in agriculture, wood preservatives, industrial water  
2 cooling towers, and many types of PVC applications). Recent evidence has been found of the  
3 direct input of MBT\* and DBT\*, most likely caused by leaching from PVC materials and  
4 house paint (Hoch, 2001). Even if the concentration ranges were quite similar for all matrices,  
5 the wastewater was characterised by a higher TBT\* proportion, whereas stormwater and CSO  
6 distributions were more readily dominated by MBT\* and DBT\*. This finding could confirm  
7 that the leaching of building materials (PCV, house paint, etc.) releases both compounds.

#### 8 *Volatile organic compounds (VOCs)*

9 Out of the 12 VOCs monitored, only tetrachloroethylene was detectable in all samples  
10 ( $2.6-9.0 \mu\text{g.l}^{-1}$ ), while ethylbenzene, toluene, xylene and trichloroethylene were occasionally  
11 detected (occurrence frequency varied from 25% to 50%). For the discharge C3 (i.e. with the  
12 highest wastewater proportion), 5 VOCs were detected vs. 1 or 2 compounds for the other  
13 discharges, thus suggesting that wastewater constitutes the major source of VOCs. The results  
14 published by Zgheib et al. (2011b, same issue), which indicate that VOCs are never  
15 quantified in stormwater except for methylene chloride ( $1.5-13 \mu\text{g.l}^{-1}$ ) and tetrachloroethylene  
16 ( $0.5-1.3 \mu\text{g.l}^{-1}$ ), along with the levels reported in the literature for wastewater (Wilkie *et al.*,  
17 1996; Rule *et al.*, 2006a) have confirmed this hypothesis. A higher number of VOCs were  
18 indeed detected in wastewater (at least 10 compounds, Fig. 1). In wastewater, methylene  
19 chloride ( $4.8-6.4 \mu\text{g.l}^{-1}$ ) and tetrachloroethylene ( $1.6-6.7 \mu\text{g.l}^{-1}$ ) were predominant, while  
20 other compounds lie in the  $0.1-2.3 \mu\text{g.l}^{-1}$  range. According to US-EPA, methylene chloride is  
21 used in various industrial processes, spanning many different industries including paint  
22 stripping, pharmaceutical manufacturing, paint remover manufacturing and metal cleaning  
23 and degreasing. Similarly, owing to its excellent degreasing properties, tetrachloroethylene is  
24 a widely preferred degreasing agent and solvent, therefore explaining its presence in  
25 numerous household products (automobile cleaners, paint removers and strippers, etc.).

## 1 *Pesticides*

2 Out of the 25 pesticides monitored, 9 corresponding for the most part to herbicides  
3 were detected in CSOs (Fig. 1). Aldrin, atrazine\* and desethylatrazine were also occasionally  
4 detected (occurrence rates of between 25% and 50%), while dieldrin (0.20-0.98  $\mu\text{g.l}^{-1}$ ),  
5 diuron\* (0.19-0.50  $\mu\text{g.l}^{-1}$ ), isoproturon\* (0.02-0.04  $\mu\text{g.l}^{-1}$ ), aminotriazole (0.13-0.46  $\mu\text{g.l}^{-1}$ ),  
6 glyphosate (0.29-1.2  $\mu\text{g.l}^{-1}$ ) and amino methyl phosphonic acid - AMPA (0.25-1.6  $\mu\text{g.l}^{-1}$ )  
7 were detected in all samples. On the whole, these pesticides were ubiquitous and found in  
8 CSOs, wastewater and stormwater. As demonstrated in Figures 1 and 2 however, pesticide  
9 patterns and levels differed depending on the matrix under consideration. The CSO discharges  
10 featured concentrations of diuron\*, isoproturon\* and glyphosate 5 to 20 times higher than  
11 those observed in wastewater, yet remaining in a range similar to what was reported by  
12 Zgheib et al. (2011b, same issue) for stormwater. It can therefore be assumed that these  
13 pollutants mainly originate from stormwater and are due to the leaching of these herbicides on  
14 impervious urban surfaces. As underscored by Blanchoud *et al.* (2004) for diuron\*, these  
15 herbicides are indeed capable of being remobilised during a rainfall event. For AMPA, the  
16 CSO concentrations were found in the lower range of what was observed for wastewater, far  
17 less than those reported for stormwater. This finding indicates that wastewater can be a major  
18 contributor of AMPA in CSOs. According to Skark *et al.* (1998), the presence of AMPA in  
19 wastewater is more likely to be correlated with the degradation of phosphonic acids in  
20 detergents than with the primary degradation of glyphosate (Skark *et al.*, 1998).

## 21 *Polyethoxylate alkylphenols (APEOs)*

22 For polyethoxylate alkylphenols (APnEOs), nonylphenols\* (NP\*, 0.6-2.2  $\mu\text{g.l}^{-1}$ ) and  
23 4-tert-octylphenol\* (OP\*, 0.1-0.2  $\mu\text{g.l}^{-1}$ ) were initially monitored in CSOs. NP\* was  
24 predominant, as compared to OP ( $10 < \text{NP}^*/\text{OP}^* < 35$ , which is in good agreement with their  
25 use and production specifications (Ying *et al.*, 2002), and mainly associated with particles

1 (from 58% to 86%). Given that APnEOs containing between 6 and 12 ethoxylate units  
2 (NPnEO and OPnEO) are the most significant from a commercial standpoint, a monitoring  
3 campaign devoted solely to both the endocrine-disrupting chemicals NP\* and OP\* is not  
4 sufficiently accurate and provides just very limited information. Complementary analyses  
5 were therefore also carried out in order to analyse NP1EO, NP2EO, OP1EO and OP2EO, as  
6 well as nonylphenol ethoxyacetic acid (NP1EC), a known degradation product of long-chain  
7 NPnEOs (Fig. 3). The concentrations found in CSOs ranged from 448 to 1,526 ng.l<sup>-1</sup> for  
8 NP1EO, from 171 to 401 ng.l<sup>-1</sup> for NP2EO, and from 221 to 591 ng.l<sup>-1</sup> for NP1EC.

9       As for PAHs or some of the pesticides, NP\* and OP\* were quantified in CSO,  
10 wastewater and stormwater, thus confirming their dissemination into the urban environment.  
11 From an overall perspective, CSOs presented similar or higher NP\* and OP\* concentrations  
12 than those found in wastewater, though exceeding by far the values reported for stormwater  
13 (Zgheib *et al.*, 2011, same issue), suggesting the contribution of in-sewer deposit erosion.  
14 This trend was confirmed by Gilbert *et al.* (2010) for long-chain APnEOs within the Paris  
15 sewer network. Although the presence of APEOs in wastewater is now well documented and  
16 related to their widespread use as surfactants in numerous industrial and commercial  
17 applications or in plastics (Ying *et al.*, 2002), the presence of APEOs in stormwater must be  
18 pointed out and these concentrations must be taken into consideration. Current knowledge on  
19 APnEO emissions in runoff is however rather limited. Based on the values reported by Zgheib  
20 *et al.* (2011b, same issue), Bressy *et al.* (2011) and Björklund *et al.* (2009) confirmed that  
21 high levels of APEOs could be found in runoff. For instance, Björklund *et al.* (2009) reported  
22 NP\* concentrations ranging from 100 (suburban residential catchment) to 1,200 ng.l<sup>-1</sup> (a high-  
23 density traffic catchment). According to both studies, the high levels of APEOs in runoff can  
24 be explained by local contributions from building and road runoff, since APEOs are used in  
25 civil engineering materials, paints and the production of sealants. The initial investigations on

1 stormwater identified levels close to 70-100 ng.l<sup>-1</sup> for NP1EO and roughly 100-140 ng.l<sup>-1</sup> for  
2 NP2EO, yet confirmation will require further experimentation. It is surprising that NP1EC,  
3 generally considered as **an aerobic** degradation product of NPnEO, were also quantified in  
4 stormwater at levels of around 300 ng.l<sup>-1</sup>; its origins need to be studied in greater detail.

#### 5 *Diethylhexyl phthalate (DEHP\*)*

6 Concentrations of diethylhexyl phthalate\* (DEHP\*) in CSOs ranged between 3.8 and  
7 14.8 µg.l<sup>-1</sup>; these values tended towards the lower range of what was reported by Gasperi *et*  
8 *al.* (2008) for CSOs in the Paris sewer network (16-57 µg.l<sup>-1</sup>, with a median of 22 µg.l<sup>-1</sup>). No  
9 clear relationship appeared between DEHP\* concentrations and the proportion of either  
10 runoff or wastewater. On the whole and given the high variability of DEHP\* concentrations,  
11 the levels found in CSOs were comparable to those measured in both wastewater (n=11, 13.1-  
12 57.3 µg.l<sup>-1</sup> with a median of 19.1 µg.l<sup>-1</sup>) and stormwater (n=14, 3.4-55.9 µg.l<sup>-1</sup>, median: 16.4  
13 µg.l<sup>-1</sup>), thus confirming the large spread of DEHP\* in the urban environment. Many studies  
14 have actually identified DEHP\* as the most frequently detected phthalate found at the highest  
15 concentrations in urban environments. As for the other chemicals, phthalates and more  
16 specifically DEHP\* are widely used throughout industry and in households, particularly as  
17 additives in plastics and PVC products pipes. According to Björklund *et al.* (2009), phthalates  
18 in runoff are likely to originate from vehicle components and reclaimed asphalt conveyed  
19 during traffic flow.

#### 20 *Chloroalkanes\**

21 Chloroalkanes\*, which are also called short-chain chlorinated paraffins (SCCP\*), have  
22 been observed in CSOs (at an occurrence rate of 75%), with concentrations ranging from 15  
23 to 50 µg.l<sup>-1</sup>. Using the same analytical methodology (with a quantification limit set at 10 µg.l<sup>-1</sup>  
24 <sup>1</sup>), chloroalkanes\* were not observed in wastewater or stormwater (Zgheib *et al.*, 2011, same  
25 issue). Even if SCCP\* are expected to be present in wastewater and CSOs since these

1 compounds are used as lubricants and additives, as well as flame retardants in a wide range of  
2 applications, no definitive conclusion can be clearly drawn for SCCP\* and moreover results  
3 must be considered carefully. As highlighted by Eljarrat and Barcelo (2006), it should be  
4 recalled that SSCP\* represent a difficult analytical problem caused by their instrumental  
5 determination and quantification, which is related to the complexity of these mixtures.

### 6 **3.3 CSO concentrations vs. Environmental Quality Standards**

7 In order to identify substances capable of representing a major risk to the environment,  
8 CSO concentrations were compared to the Environmental Quality Standards (EQS)  
9 established by the European Commission (Table 5). The relevant Directive defines two types  
10 of standards: i) the annual average concentration (EQS-AAC) of the substance over a 1-year  
11 period, and ii) the maximum allowable concentration (EQS-MAC) of the substance measured  
12 at specific points in time. As previously described by Zgheib *et al.* (2011), this approach was  
13 simple and easy, yielding an indicative rate of dilution required in the receiving environment  
14 for compliance with the WFD. Of the substances quantified in CSOs for which an EQS has  
15 been proposed, a limited number may pose environmental risks as regards compliance with  
16 standards established at the European level. No risk of exceeding EQS-AAC and EQS-MAC  
17 was observed for tri- and tetra-chloroethylenes, atrazine\*, isoproturon\*, octylphenol\*,  
18 anthracene\* and naphthalene\* ( $F < 1$ ), while only a limited risk was observed for diuron\*,  
19 DEHP\*, nonylphenols\*, benzo(a)pyrene\* and fluoranthene\* ( $1 < F < 10$ ). On the other hand,  
20 major dilution factors were required for PAHs (sum of B(b)F\* + B(k)F\* and sum of IP\* +  
21 B(ghi)P\*, only for EQS-AAC) and, to a greater extent, for tributyltin compounds\* (TBT\*,  
22 DBT\* and MBT\*) and chloroalkanes\* in terms of both EQS-AAC and EQS-MAC. As for  
23 EQS-MAC, tributyltin\* should be carefully considered, since a significant dilution factor was  
24 required (from 19 to 300). For chloroalkanes\*, dilution factors were lower yet remained  
25 between 10 and 35.

## 4. Conclusion

This study, as part of the OPUR research programme, has been aimed at investigating the quality of combined sewer overflow in urban watersheds. By monitoring priority pollutants as well as additional substances, this study constitutes the first relevant approach to providing accurate knowledge on the occurrence and concentrations of a broad spectrum of pollutants in CSOs and their significance compared to wastewater and stormwater.

This work has served, first and foremost, to confirm that a wide range of PPs are indeed present in CSOs. Of the 88 stormwater priority substances monitored in both the particulate and dissolved phases, 49 different PPs, including 19 priority hazardous substances\*, could be detected. Most of these were also frequently observed in wastewater and stormwater, thus confirming that PPs are now ubiquitous in our urban environment. Nevertheless, some differences relative to concentration ranges and/or pollutant patterns from one matrix to the next can still be drawn. For most hydrophobic organic pollutants, such as PAHs and APnEOs, and some preferentially particulate-bound metals (Pb\* and Cu), CSOs exhibit higher concentrations than those found in stormwater and wastewater. As previously demonstrated, this result is highly correlated with the significant in-sewer deposit erosion. For less hydrophobic pollutants, such as pesticides or preferentially dissolved metals like Zn, CSOs yield concentrations close to stormwater, thus suggesting that runoff is the major contributor while wastewater and in-sewer processes remain minor sources. For VOCs, wastewater seems to be the major contributor in CSOs since these compounds were not detected in stormwater. Similar concentration ranges were found for DEHP and tributyltin compounds\* in CSOs, wastewater and stormwater as a result of their high inter-event variability. Lastly, a comparison of CSO concentrations with European standards underscores that CSO discharges may pose a significant environmental risk as regards PAHs, tributyltin

1 compounds\* and chloroalkanes\*, since high dilution factors were required to comply with  
2 EQS-AAC or EQS-MAC. Further investigation is now required to better evaluate this risk.

3 By providing significant knowledge on the quality of CSO, wastewater and  
4 stormwater, this study and, more generally, the data provided by the OPUR research  
5 programme might be used in the future to identify PPs of potential significance. In the near  
6 future, such data could also serve to establish accurate mass balances in order to apportion the  
7 contributions of wastewater, runoff and in-sewer deposit erosion to CSO loads in combined  
8 sewers. This information will soon be of prime importance in reducing priority pollutant  
9 discharges within the urban environment and as part of the effort to prioritise "control at the  
10 source" interventions. Among the various issues on the horizon, one OPUR research  
11 programme priority will consist of investigating the occurrence and significance of priority  
12 pollutants in atmospheric inputs, so as to better understand the role of atmospheric fallout in  
13 urban environmental contamination.

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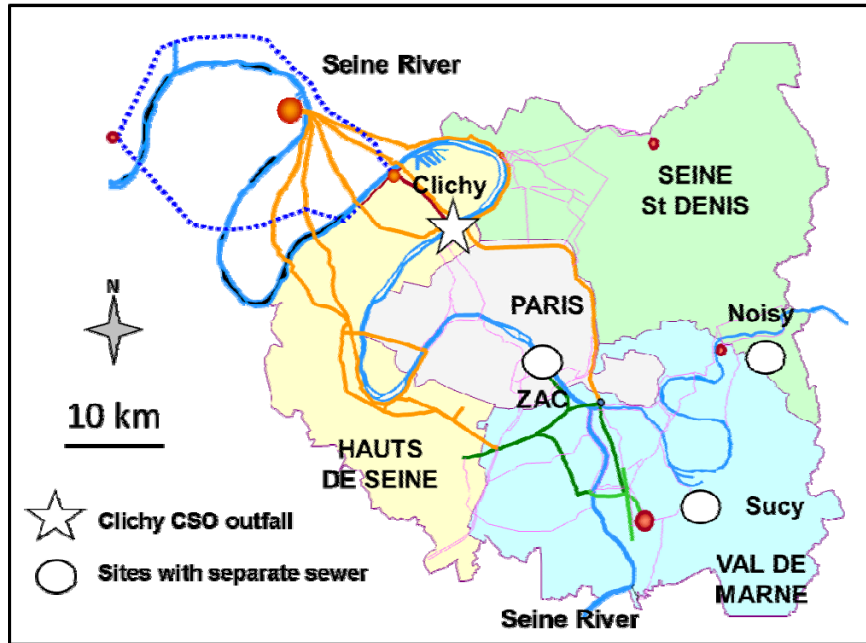
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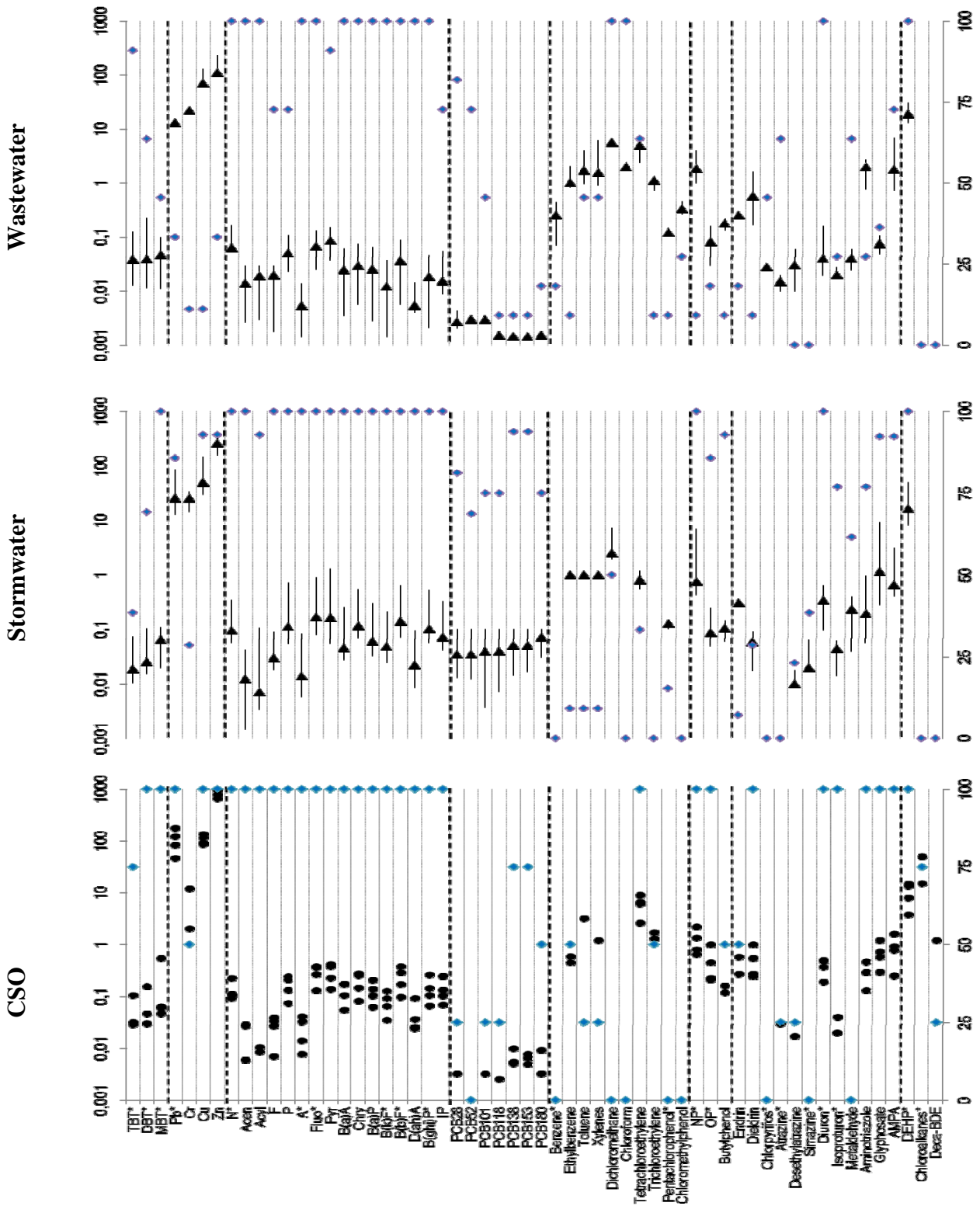
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**Figure 1: Sites considered within OPUR research program. The Clichy outfall was considered for CSO, while Noisy, Sucy and ZAC sites were dedicated to study the stormwater quality in connection with the urbanisation gradient (Zgheib et al., 2011a)**

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 3 Figure 2: Total concentration ( $\mu\text{g.L}^{-1}$ , left axis) for CSOs (n=4), wastewater (n=11) and stormwater in  
 4 a separated sewer (n=17), as well as occurrence rates (blue lozenges, in %, right axis). CSO samples  
 5 were collected in 2010, wastewater in 2009-2010, and stormwater over the 2008-2010 period. For  
 6 stormwater and wastewater, lines illustrate the first and last decile concentrations (d10 and d90),  
 7 and black triangles refer to median (d50).  
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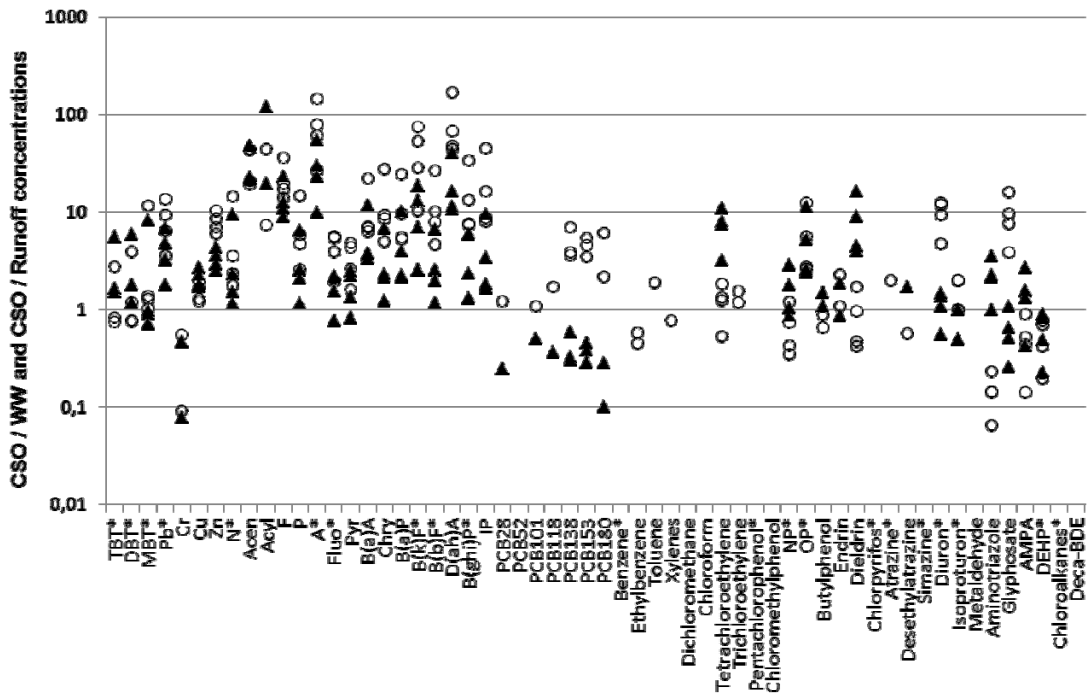


Figure 3: Ratios between CSO and median wastewater concentrations (white circles) and between CSO and median stormwater concentrations (black triangles)

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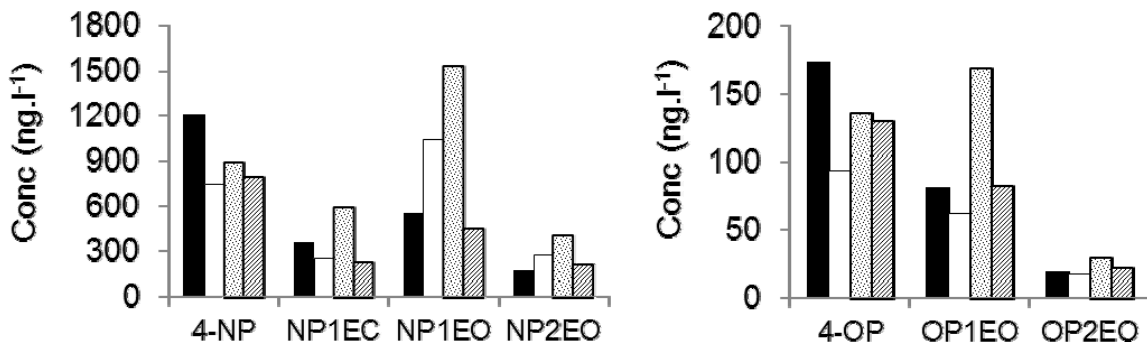


Figure 4: APnEOs concentrations (ng.l<sup>-1</sup>) in CSOs (C1, C2, C3 and C4)

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2 **Table captions**

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Table 1: Main characteristics of the rain events studied and runoff proportions

Date		H <sup>1</sup> (mm)	Volume (m <sup>3</sup> )	ADP <sup>2</sup> (d)	Cond <sup>3</sup> ( $\mu\text{S.cm}^{-1}$ )	Runoff (%) <sup>4</sup> Min-Max
2010/07/12	C1	32.9	559,390	9	284	78-87
2010/07/14	C2	43.1	1,005,150	2	201	87-95
2010/09/08	C3	13.2	39,200	16	380	69-77
2010/09/24	C4	16.5	325,175	16	260	75-89

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(1)  $H$  = precipitation height for each rain event (mm), (2) ADP = antecedent dry period, time period since the previous rain event (day), (3) Cond = conductivity, in  $\mu\text{S.cm}^{-1}$ , (4) runoff proportion, estimation based on conductivity measurement.

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Table 2: List of monitored priority pollutants and analytical methods

Groups <sup>1</sup>	Total <sup>2</sup>	Standards	Methods <sup>3</sup>	Phase <sup>4</sup>
Alkylphenols	5 (2)	ISO 18857-1	GC-MSMS	P + D
BTEX	5 (1)	NF EN ISO 11423-1	GC-MS	T
Chloroalkanes	1 (1)	Internal method	GC-ECD	P + D
Chlorobenzenes	5 (3)	EN ISO 6468	GC-MS	P + D
Chlorophenols	1 (1)	NF EN 12673 + ISO 6468	GC-MSMS	P + D
HVOCs	7 (4)	NF EN ISO 10301 + 6468	GC-MS	T
PAHs	16 (8)	ISO 17993	HPLC-Fluo	P + D
Metals	8 (4)	NF EN ISO 11885 + 1483	ICP and AAS	T + D
Organotins	3 (3)	NF EN ISO 17353	GC-MS	P + D
PBDEs	3 (1)	ISO 22032	GC-ECD	P + D
PCBs	8	NF EN ISO 6468	GC-MS-MS	P + D
Pesticides	25 (12)	NF EN ISO 11369 + Internal method	GC-MS UPLC-MSMS	P + D
Phthalates	1 (1)	Internal method	GC-MS	P + D

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(1) Compound groups: BTEX = benzene\*, toluene, ethylbenzene and xylenes, HVOC = halogenated volatile organic compounds, PAHs = polycyclic aromatic hydrocarbons, PBDE = polybromodiphenylethers, PCB = polychlorinated biphenyls, (2) The substance in brackets is listed in the WFD, (3) Analytical methods: ICP = inductively coupled plasma, AAS = atomic absorption spectrometry, GC = gas chromatography, GC-ECD = GC with electron capture detector, GC-MS = GC with mass spectrometer, GC-MSMS = GC gas chromatography with tandem mass spectrometer, HPLC-fluo = High pressure liquid chromatography with fluorescent detector, UPLC-MSMS = ultra performance liquid chromatography with tandem mass spectrometer, (4) Phase considered with: D = dissolved, P = particulate, T = Total.

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Table 3: Wastewater quality parameters for the studied CSO discharges

	C1	C2	C3	C4	CSO database <sup>1</sup>	WW database <sup>2</sup>	Runoff <sup>3</sup>
TS mg.l <sup>-1</sup>	193	135	353	153	121-394 237	190 – 314 252	30-75 36
COD mg O <sub>2</sub> .l <sup>-1</sup>	254	136	446	260	157-491 336	322-520 436	43-113 56
BOD <sub>5</sub> mg O <sub>2</sub> .l <sup>-1</sup>	78	36	180	95	54-200 135	130-230 180	8-25 11
TKN mg N.l <sup>-1</sup>	17	7.2	27	18	15-37 22	31-49 41	< 4
NH <sub>4</sub> <sup>+</sup> mg N.l <sup>-1</sup>	6.4	3.3	9.3	8.1	5.8-22.2 9.9	20-32 28	-
PO <sub>4</sub> <sup>3-</sup> mg P.l <sup>-1</sup>	0.8	0.5	1.4	1.1	0.8-2.2 1.2	2.0-3.0 2.6	-
P <sub>tot</sub> mg P.l <sup>-1</sup>	2.7	1.2	5.4	3	2.3-5.4 3.5	4.1-6.4 5.4	-

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(1) CSO database from SIAAP (n=52) for the 2009-2010 period, (2) Wastewater database from SIAAP on the Clichy site (n=460), (3) runoff, data from Kafi et al. (2008). *For CSO database, wastewater database, and runoff rows, first line refers to d10 and d90 concentrations; second line is median concentration (d50.)*

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1 Table 4: Pollutants detected and undetected in CSOs

Never detected in CSOs, wastewater and runoff or when detected with an occurrence < 15% (30 PPs, incl. 14 PHS*)	Cd*, Hg*, Ni*, Pt dichloroethane*, trichlorobenzenes* (3), pentachlorobenzene*, hexachlorobenzene*, carbon tetrachloride, isopropylbenzene hexachlorobutadiene*, hexachlorocyclohexane* endosulfan* (2), alachlor*, isodrin, lindane*, chlorfenvinphos*, desethylsimazine, endrin, trifluralin*, DDT (2) PCB 194, octa-BDE, penta-BDE, 4-n-octylphenol*, 4-para-nonylphenol
Undetected in CSOs, but detected in wastewater and runoff (9 PPs, incl. 5 PHS*)	chloromethylphenol, benzene*, chloroform*, dichloromethane*, chlorpyrifos*, simazine*, metaldehyde, PCB 52, pentachlorophenol*
Detected in CSOs (49 PPs, incl. 19 PHS)	4 metals (Pb*, Cr, Cu, Zn) 5 COVs (ethylbenzene, toluene, xylenes, tetrachloroethylene, trichloroethylene) 9 pesticides (aldrin, dieldrin, atrazine*, desethylatrazine, diuron*, isoproturon*, aminotriazole, glyphosate, AMPA) 3 organotins (TBT*, DBT*, MBT*) 3 alkylphenols (nonylphenol*, octylphenol*, butylphenol) 16 US-PAHs (N*, Acen, Acyl, F, P, A*, Fluo*, Pyr, B(a)A, Chry, B(a)P*, B(b)F*, B(k)F*, D(ah)A, B(ghi)P*, IP*) 7 PCBs (28, 101, 118, 138, 153 and 180) Deca-BDE, chloroalkanes*, DEHP*

2 *In parentheses: Number of congeners considered, \* for priority hazardous substances*

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Table 5: Ratios of CSO concentrations and EQS-AAC or EQS-MAC

	CSO concentration / EQS-AAC	CSO concentration / EQS-MAC
Undetected	24 PPs	15 PPs
< 1	7 PPs: tri- and tetra-chloroethylenes atrazine*, isoproturon* octylphenol* anthracene*, naphthalene*	8 PPs: tri- and tetra-chloroethylenes atrazine*, isoproturon*, diuron* nonylphenols* anthracene*, fluoranthene*
1 - 10	5 PPs: diuron*, DEHP*, nonylphenols*, benzo(a)pyrene* fluoranthene*	1 PP: benzo(a)pyrene*
10 - 100	4 PPs: aldrin, dieldrin, chloroalkanes* Sum of B(b)F* + B(k)F*	4 PPs: TBT*, DBT*, MBT* chloroalkanes*
> 100	4 PPs: TBT*, DBT*, MBT* Sum of IP* + B(ghi)P*	-

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