Settling velocity of particulate pollutants from combined sewer wet weather discharges
M. C. Gromaire, M. Kafi-Benyahia, J. Gasperi, M. Saad, R. Moilleron and G. Chebbo

ABSTRACT
Settling velocities of TSS and of particulate pollutants (COP, PDCO, PTKN, PCu, PPb, PZn, PPAH) measured on a wide range of wet weather flow (WWF) samples collected at different levels of the Parisian combined sewer system are reported. The recorded V30 (0.01 to 0.1 mm.s⁻¹) and V50 (0.09 to 0.6 mm.s⁻¹) values exceed by a factor 10 those of dry weather sewage and also exceed the values measured for pavement runoff. These values lie however often below the 0.28 mm.s⁻¹ reference value considered in France for the design of WWF settling facilities. A decrease in settleability is observed between a small upstream catchment and larger scaled downstream catchments. The settling behaviour of particulate pollutants varies depending on the considered parameter and can differ significantly from the TSS behaviour, due to a non homogeneous distribution of micropollutants over the different classes of particles. PZn and PTKN appear far less settleable than TSS, whereas PPAH show higher settleability.

Key words | combined sewer, metals, organic matter, PAH, runoff, sedimentation, settling velocity, VICAS, VICPOL, wet weather flows

NOMENCLATURE

EIQR relative interquartile deviation,
EIQR = (Q3 − Q1)/Q2 * 100 with Q1 is the 1st quartile, Q2 is the median, Q3 is the 3rd quartile
F(Vs) cumulative percentage of the total mass of particles with a settling velocity of less than Vs, %
PAH Polycyclic aromatic hydrocarbons
PCOD particle bound chemical oxygen demand, mg.l⁻¹
PCu particle bound copper concentration, μg.l⁻¹
PPH particle bound polycyclic aromatic hydrocarbons, μg.l⁻¹
PPb particle bound lead concentration, μg.l⁻¹
PTKN particle bound total Kjeldahl nitrogen, mg.l⁻¹
PZn particle bound zinc, μg.l⁻¹
TSS total suspended solids concentration, mg.l⁻¹ (mass retained on a Whatman GF/F 0.7 μm glass fibre filter)
Vs settling velocity, mm.s⁻¹
The majority of pollutants contained in urban effluent during wet periods are associated with particles (Ashley et al. 2004; Kafi et al. 2008; Marsalek et al. 2006; Pitt et al. 1995). Moreover, the particles being transported in suspension via urban discharge during wet weather also appear to be easily settleable despite their relatively fine particle size distribution, as characterized by a median diameter from 30 to and 40 \( \mu \text{m} \) (Chebbo & Bachoc, 1992). Consequently, settling is often favoured when installing effluent treatment systems operating in wet weather conditions.

The design and layout of these facilities, as well as the description of solid transport phenomena in numerical simulation tools, requires a good knowledge of the nature of suspended solids (TSS): this would start with the sedimentation velocity of particles and include the sedimentation velocities of a range of pollutants associated with these particles. The distribution of pollutants might not necessarily be uniform for the entire set of particles. A number of authors have pointed out the propensity of micropollutants such as metals and PAH to bond with the smallest-sized particles (Colandini et al. 1995; Krein & Schorer, 2000; Sansalone & Buchberger, 1997). Consequently, settling efficiency is capable of varying depending on the particulate pollutant under consideration.

Data relative to the settling velocity of stormwater TSS have been acquired over the past fifteen years or so (Chebbo & Bachoc, 1992; Hedges et al. 1998; Michelbach & Wöhrl, 1992; Pisano, 1996). The databases available however remain limited in scope when compared with the variability in phenomena from one rainfall event to another and from one measurement site to another. Major disparities have been observed between the results derived from different research teams and these may be ascribed in part to differences in the measurement protocols employed (Lucas-Aiguier et al. 1998). The most recent set of results (Chebbo & Gromaire, 2004) adds further credence to downplaying the postulate of “highly settleable stormwater”, which had enjoyed considerable support since the 1990s.

Furthermore, the settling behaviour of a variety of pollutants attached to particles has only rarely been studied. Some partial results have been provided (Benoist & Lijklema, 1990; Michelbach & Wöhrl, 1993; Tyack et al. 1992) for heavy metals. The inconsistencies noticed in these different results could be attributed to sample discrepancies as well as to differences in test procedures or uncertainties, even inaccuracies, induced by these disparate test procedures.

One of the objectives inherent in the research project entitled “Spatial evolution of characteristics and pollutant sources in combined sewer networks” (programme code: OPUR2, “Observatory of Urban Pollutants”, supervised by Cereve between 2001 and 2006) sought to better comprehend the characteristics of particles being transported during rainy periods through the Paris sewer network at various spatial scales, in order to:

- compile, by use of an identical and reliable measurement protocol, a database relative to the sedimentation velocity of TSS within combined sewer effluent during wet weather; and
- provide a series of initial elements regarding the distribution of pollutants by settling velocity category, which in turn are capable of yielding the settleability of these pollutants.

This article summarizes the OPUR2 research project results obtained in terms of: TSS settling velocity in combined sewer effluent during wet weather; settling velocity of particulate organic matter (PCOD, POC), particulate nitrogen, particulate metals (PCu, PPb, PZn) and particulate PAH; and distribution of these particulate pollutants by category of TSS settling velocity.

**MATERIALS AND METHODS**

Protocols adopted to measure the settling velocity of urban effluent

Description of measurement protocols

Results published by Lucas-Aiguier et al. (1998) revealed the need to perform stormwater settling velocity measurements...
immediately after sampling, under conditions similar to those of the initial effluent (type of water, concentration) and without any sample pretreatment. Similar conclusions had already been drawn by Phillips & Walling (1995) for fluvial suspended sediments. Most settling column tests cited in the literature for stormwater settling velocity measurements do not meet these criteria. Two settling velocity measurement protocols, intended to characterize urban stormwater effluent, were thus developed at the Cereve research centre. Assigned the names VICAS and VICPOL, these protocols have been designed so as to enable measuring sedimentation velocities directly on the raw effluent (without any test sample pretreatment that could potentially alter particle characteristics), immediately after sampling (in order to avoid bias due to specimen handling and conservation). Both protocols feature a relatively straightforward approach quick to implement (making it possible to process samples on the spot, while inciting widespread dissemination of this type of measurement) and require just a minimal sample volume (i.e. compatible with the smaller volumes typically collected during a rainfall event using a portable automatic sampler).

The two protocols are based on a column sedimentation measurement using still water and proceed according to the principle of homogeneous suspension.

VICAS. The VICAS protocol (Chebbo & Gromaire, submitted) allows, by means of a space-efficient, inexpensive and easy-to-handle sedimentation column, conducting the TSS settling velocity measurement on a reduced volume sample (4.5 litres).

At the initial time, the sedimentation column is filled with a homogeneous effluent mix, with particles thus being uniformly distributed over the entire sedimentation height. The solids that had settled during a predefined time interval are then recovered on the bottom of the column. Their mass is weighed, which serves to determine the evolution in cumulative mass $M(t)$ of the deposit vs. time $t$. A theoretical analysis indicates that the $M(t)$ curve may be expressed in the following form:

$$M(t) = S(t) + t \frac{dM(t)}{dt}$$

(1)

where $M(t)$ is cumulative mass of particles settled at the base of the column between $t = 0$ and $t$, $S(t)$ is mass of the particles settled between $t = 0$ and $t$ that possess a settling velocity greater than $H/t$, where $H$ is the column water height, $tdM/dt$ is mass of the settled particles at time $t$ that possess a settling velocity less than $H/t$. The measurement procedure enables determining the $S(t)$ curve and then transforming it into the $F(V_s)$ curve, which shows the cumulative percentage $F$ (expressed as a %) of the total mass of particles, with a settling velocity of less than $V_s$ (in mm.s$^{-1}$).

A complete description of the VICAS protocol has been provided by Chebbo et al. (2003)

VICPOL. The VICPOL protocol (Gromaire et al. 2007) focuses on measuring the sedimentation velocity of the pollutants and micropollutants associated with particles. Protocol implementation requires a much more substantial sample volume: 20-litre minimum.

The principle herein is to track the decrease in concentration $Ci$ vs. decantation period $ti$ at a given point of the sedimentation column, which is to be initially filled with a homogeneous suspension of the sample under analysis. VICPOL introduces 5 sedimentation columns, each fitted with a device to allow extracting, once a decantation time $ti$ (different for each column) has elapsed, a horizontal water slice corresponding to an average settling height of 40 cm and a 750 ml volume (Figure 1). The percentage of particles with a settling velocity of less than $V_s$ is given directly by: $F(V_s) = 100 \frac{Ci}{Coi}$, where $Ci$ denotes the particulate pollutant concentration measured on the sample extraction performed in column $i$, after an elapsed decantation time of $ti$, and $Coi$ is the particulate pollutant concentration measured on a sample extracted during filling of this same column $i$.

VICPOL settling columns are filled by gravity, which serves to limit sample modifications and hydraulic disturbances due to the feeding operation. The use of five smaller settling columns was preferred to a successive sampling within a single larger column. Preliminary tests with dies and seed particles actually displayed sizable hydraulic recirculations inside the settling column following sample retrieval. Moreover, it proves easier to achieve initial concentration homogeneity inside a small column as opposed to a very large one. In our test campaign, differences between the initial reference concentration and
initial concentrations measured for the five columns tended to remain within a margin of ±7%. VICPOL results appear to show little sensitivity either to this small initial inhomogeneity or to analytical uncertainties (Gromaire et al. 2007).

The VICPOL protocol was applied to the following pollutants: COD, POC, PTKN, PCu, PPb, PZn, and PPAH. In the case of POC and PPAH, concentrations are directly measured on the particles themselves. For COD, TKN and metals on the other hand, particulate concentrations are determined by means of differences between total concentration and concentration of the dissolved fraction (filtered at 0.45 µm).

**Uncertainty in the settling velocity measurement**

Uncertainties in the settling velocity measurements associated with the VICAS and VICPOL protocols were evaluated on the basis of repeatability tests conducted on combined sewer effluent samples during wet weather conditions. Reproducibility of the VICAS protocol was assessed using six replicates from a single sample, by setting up six VICAS columns in parallel. Repeatability of the VICPOL protocol was evaluated for three different settling times: 8 min, 22 min and 4 hours. For each of these times, ten replicates were produced in parallel using ten VICPOL columns. The parameters analyzed herein were: TSS, POC, and COD.

These tests indicate a good level of repeatability in the measured settling velocities. In the case of VICAS, uncertainties at the 95% confidence band tend to decrease with higher measured settling velocities; they vary from ±14.8% ($V_s < 0.01 \text{mm.s}^{-1}$) to ±1.4% ($V_s < 10 \text{mm.s}^{-1}$). For VICPOL, measurement uncertainties on $F(V_s)$ at the 95% confidence threshold are at most on the order of ±14% for TSS, ±21% for PCOD and ±16% for POC.

**Intercomparison between the two protocols**

Intercomparison tests on the two protocols, in terms of TSS and POC settling velocities, were carried out for four rainfall events. A comparison of settling velocity distributions obtained by both protocols does not reveal any significant differences, with deviations in all cases remaining less than the above mentioned measurement uncertainties.

**Description of the study samples**

**Samples studied with respect to TSS and POC settling velocities**

TSS and POC settling velocity measurements were taken on 30 event-mean samples from combined sewer WWF...
The samples were collected at the outfalls of the various OPUR2 catchment basins in Paris. The characteristics of these basins (land area, population served, pipe lengths), along with the description of sampling systems, have been detailed by Kafi et al. (2008).

The pluviometric characteristics of the various rainfall events corresponding with these 30 samples are listed in Table 1.

It needs to be stated however that the samples were collected in large part at the outfalls of just two of the catchment basins, which happen to reflect two distinct spatial scales: the Marais (42 ha - 13 analyzed rainfall events) and Clichy (942 ha - 8 rainfall events). Six rainfall events were simultaneously studied over these two catchments and utilized for analyzing spatial variability in terms of TSS and POC settling velocities.

In addition, the TSS settling velocities of wastewaters during dry weather periods were determined for 11 average daily samples collected at the outfalls of the various OPUR2 catchment basins.

We also incorporated into this analysis the settling velocities measured during the 1996-1997 campaign, through application of the VICAS protocol on 51 average pavement runoff samples collected on six streets of the Marais basin in Paris (Gromaire-Mertz, 1998).

### Assessment of samples studied in terms of pollutant and micropollutant settling velocities

The sedimentation velocities of TSS, POC, particulate COD (PCOD), particulate TKN (PTKN) and particulate metals (PCu, PPb, PZn) were all measured using the VICPOL protocol, for 7 rainfall events sampled at the outfall of the Marais catchment and for 2 rainfall events sampled at the outfall of the Clichy catchment. The characteristics of these samples, in terms of TSS concentration, organic matter and nitrogen content, along with metal content of the particles, are listed in Table 2. These concentrations and contents vary considerably from one sample to the next and cover the entire range of values recorded over the series of OPUR2 measurement campaigns (Kafi et al. 2008).

The settling velocity of particulate PAH (using the sum of the 6 PAHs cited in the European Water Framework Directive 2000/60/CE, i.e. fluoranthene, benzo(a)pyrene, benzo(b)fluoranthene, benzo(k)fluoranthene, indeno(123)-pyrene, benzo(ghi)perylene) were measured in parallel with the TSS settling velocity, according to the VICPOL protocol, for 4 rainfall events sampled at the Marais outfall and for 3 events sampled at Clichy. Both the TSS concentrations and PAH contents are given in Table 3. Here once again, the samples cover a diverse range of concentrations, corresponding with the range identified during the OPUR2 research program in wet weather effluent (Gasperi, 2006; Gasperi et al. 2007).

### RESULTS AND DISCUSSION

#### TSS and organic carbon settling velocities

**Order of magnitude for the V50 and V30 deciles**

The orders of magnitude for settling velocities measured in the OPUR study zone’s combined sewer effluent are shown in Table 4. They have been compared with values measured

<table>
<thead>
<tr>
<th>TSS mg.l⁻¹</th>
<th>POC/TSS g.C.g⁻¹</th>
<th>PCOD/TSS g.g⁻¹</th>
<th>PTKN/TSS gN.g⁻¹</th>
<th>PCu/TSS mg.g⁻¹</th>
<th>PPb/TSS mg.g⁻¹</th>
<th>PZn/TSS mg.g⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum 154</td>
<td>0.28</td>
<td>0.82</td>
<td>0.02</td>
<td>0.33</td>
<td>0.30</td>
<td>3.13</td>
</tr>
<tr>
<td>Median 288</td>
<td>0.37</td>
<td>1.31</td>
<td>0.03</td>
<td>0.43</td>
<td>0.59</td>
<td>4.04</td>
</tr>
<tr>
<td>Maximum 509</td>
<td>0.44</td>
<td>1.63</td>
<td>0.06</td>
<td>0.66</td>
<td>1.25</td>
<td>5.76</td>
</tr>
</tbody>
</table>
at the Marais outfall during 1996-1997 and with the settling velocities determined by implementing the VICAS protocol on an array of other sites. Let’s recall at this point that the V50 designation corresponds to the settling velocity exceeded by 50% of the particles according to their mass (or 50% in mass terms of the particulate fraction for the given pollutant), and V30 corresponds to the settling velocity exceeded by 70% in mass terms of the particles (or 70% in mass of the pollutant particulate fraction).

The median values derived from the OPUR2 project equal 0.05 mm.s$^{-1}$ for V30 and 0.24 mm.s$^{-1}$ for V50. These settling velocities display the same order of magnitude as those previously measured on the Marais catchment and lie within the range of values observed for other French combined sewer networks (see Table 4). The V50 values measured at the outfall of the Marais site in 2004-2005 appear to be a bit higher than those found in 1996-1997. The difference however is not statistically significant (Mann-Whitney test, p > 0.05) and could be ascribed to dissimilarities in the characteristics of rainfall events included in the study.

It should be noted that the V30 of combined sewer effluent typically lies well below a value of 1 m.h$^{-1}$, i.e. 0.28 mm.s$^{-1}$, which is still set as the reference in France when designing settling structures based on the initial settling velocity of wet weather urban discharges obtained by Chebbo & Bachoc (1992).

A strong level of variability in both V30 and V50 is observed from one rainfall event to another, with a factor of 5 to 10 between the 1st decile and the 9th. For some rainfall events, a fraction of TSS proves difficult to settle. This phenomenon had been previously detected by Chebbo, who identified minimum V20 values lying on the order of 0.017 mm.s$^{-1}$, yet this threshold is not always taken into account when evaluating the efficiency of treating wet weather urban discharge by sedimentation.

### Variability of settling velocities as a function of the spatial scale

The comparison of settling velocities measured for the same seven rainfall events on the Marais and Clichy catchment basins reveal settling velocities systematically lower on the Clichy basin (see Figure 2). Application of the Wilcoxon test (p < 0.05) on paired samples shows that the Marais settling velocities are statistically higher than those recorded on Clichy. The median value of V50 is 0.45 mm.s$^{-1}$ for Marais and 0.21 mm.s$^{-1}$ for Clichy. Furthermore, the dispersion in V50 values is slightly greater on the Marais site, with a relative interquartile deviation EIQr of 91% vs. 80% for Clichy. The smallest settling velocities recorded on the Clichy site, in comparison with the Marais site, are not apparently explainable by a difference in transport capacity, since the flow speeds over the Clichy zone tend to be much higher than those measured for the Marais.

The variability in settling velocities vs. catchment basin spatial scale has also been analyzed for three other rainfall events during which simultaneous settling velocities were measured on three OPUR2 project catchment basins. While the Marais (42 ha) combined sewer effluent settles significantly faster than that of the other test sites, settling

### Table 3 | Characteristics of the analyzed samples regarding the settling velocity of PPAH

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>TSS mg.l$^{-1}$</th>
<th>PPAH/TSS μg.g$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>191</td>
<td>1.67</td>
</tr>
<tr>
<td>Median</td>
<td>274</td>
<td>4.66</td>
</tr>
<tr>
<td>Maximum</td>
<td>448</td>
<td>9.48</td>
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</table>

### Table 4 | Orders of magnitudes for settling velocities (10% percentile – 90% percentile, median) in combined sewer effluent during wet weather conditions

<table>
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</thead>
<tbody>
<tr>
<td>N</td>
<td>32</td>
<td>13</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>V30 (mm.s$^{-1}$)</td>
<td>0.01 – 0.10</td>
<td>0.02 – 0.17</td>
<td>0.03 – 0.18</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.05</td>
<td>0.07</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>V50 (mm.s$^{-1}$)</td>
<td>0.09 – 0.58</td>
<td>0.22 – 0.7</td>
<td>0.13 – 0.53</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.24</td>
<td>0.43</td>
<td>0.30</td>
<td></td>
</tr>
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($^*$) Aires et al. 2003; DSEA (2003); Jaumouillie, 2002; Ruscassier, 1996
velocities, in contrast, proved comparable among the three downstream sites Clichy (942 ha), Coteaux (1315 ha) and Clichy-downstream (2581 ha), which suggests phenomenon stabilization once a certain spatial scale has been reached (see Figure 3).

The difference in settling velocity between the Marais catchment and larger-sized catchments may be ascribed to a higher proportion of wastewaters within the combined sewer effluent of larger catchment basins. Kafi-Benyahia (2006) indeed recorded an increase in the contribution from wastewaters into wet weather TSS flows with respect to the basin spatial scale. Figure 4 indicates the decreasing trend of V30 settling velocity as the proportion of TSS stemming from wastewaters present in the combined network effluent increases. This trend is much less pronounced for V50.

In order to verify whether the spatial variability of settling velocities found in combined sewer effluent was actually attributable to variability in the proportion of TSS stemming from wastewaters, we recalculated the settling velocity distribution of particles not originating from wastewaters (denoted herein “storm”), on the basis of:

- the settling velocity distribution of combined sewer effluent for each rainfall;
- the average settling velocity distribution of wastewaters, as measured on dry weather effluent (as shown in Figure 6, the settling velocity of wastewaters only varies slightly from one sample to the next in comparison with velocity measurements for the combined sewer effluent); and,
- the percentage of TSS assignable to wastewaters for each rainfall event.

The results obtained in terms of V30 are summarized in Figure 5. Subtracting the wastewaters TSS leads to an increase in V30 for the two sites, yet does not serve to eliminate the difference existing between sites for all rainfalls. However, the difference in terms of V30 for the “storm” effluents of both sites remains statistically insignificant according to the Wilcoxon test.

The contribution calculations performed by Kafi-Benyahia (2006) for the OPUR zone have demonstrated that the stormwater contribution to TSS flows during wet periods is relatively slight (9% to 12%) and that regardless of the catchment basin under consideration, the major share of TSS originates from the erosion of organic deposits in the network (47% to 69%). Moreover, authors reported that the type of eroded deposits seems to be homogeneous across the various basins in terms of
organic matter content. Oms (2003) also observed that the erosion of organic deposits within Marais zone sewer pipes took place by packets of matter, subsequently transported as both suspended load and bed load. The highest settling velocities measured over the Marais basin might therefore also be explained by means of a gradual disaggregation of eroded particles during their transport between the upstream and downstream catchment basins.

Comparison of TSS settling velocities from combined sewer effluent with velocities from wastewaters and runoff

The V50 settling velocities of OPUR combined sewer effluent during wet weather were compared with the V50 values for OPUR study area wastewaters and pavement runoff water in the Marais zone (Figure 6). It can be observed that the sedimentation velocities of wet weather combined sewer effluent are not only markedly greater than the same velocities for wastewaters (by a factor of around ten on the median value), but also lie above the settling velocities of runoff (by a factor of 2 on the median value, with the Mann-Whitney test confirming a statistically significant difference).

We have also recalculated the V50 settling velocity of wet weather effluent after subtracting the wastewaters contained in the combined network effluent. The V50 settling velocities of this type of “stormwater” show a median of 0.4 mm.s\(^{-1}\), which makes them statistically greater than the runoff velocities (Mann-Whitney test, \(p < 0.05\)). This finding can only be explained by a contribution of particles with high settling velocities stemming from the erosion of organic deposits during transfer within the wastewaters network.

Settling behaviour of the particulate pollutants and micropollutants

Settling velocities of pollutants and micropollutants

The orders of magnitude of both the V30 and V50 settling velocities, as measured for the same 9 samples in terms of TSS, particulate organic matter, particulate metals and
particulate nitrogen have been depicted in Figure 7. Figure 8 serves to compare the orders of magnitude for the V30 and V50 settling velocities measured on 6 other samples, and this time in terms of TSS and PPAH.

The median value of V50 is respectively 0.38 mm.s\(^{-1}\) for TSS, 0.39 mm.s\(^{-1}\) for PCOD, 0.47 mm.s\(^{-1}\) for POC, 0.28 mm.s\(^{-1}\) for PCu, 0.17 mm.s\(^{-1}\) for PPb, 0.09 mm.s\(^{-1}\) for PZn and PTKN, and 0.74 mm.s\(^{-1}\) for PPAH.

The median value of V30, on the other hand, is respectively 0.07 for TSS, 0.04 mm.s\(^{-1}\) for PCOD, 0.10 mm.s\(^{-1}\) for POC, 0.06 mm.s\(^{-1}\) for PCu, 0.03 mm.s\(^{-1}\) for PPb, 0.02 mm.s\(^{-1}\) for PZn and PTKN, and 0.23 mm.s\(^{-1}\) for PPAH.

The variability from one rainfall event to the next in the V50 and V30 values for particulate pollutants is greater than that for TSS. The relative interquartile deviations EIQR lie on the order of 40% to 70% for TSS and POC, 100% to 200% for PCOD, PCu, PZn and PTKN, and over 200% for PPb.

Based on a comparison of the settling velocity curves of the various pollutants, with special emphasis on the ratio of V30 for TSS to V30 for pollutants (Figure 9), four pollutant groups can be distinguished:

- particulate organic carbon displays a settling behaviour nearly identical to that of TSS;
- particulate COD, copper and lead exhibit a variable behaviour from one rainfall event to another. For the
Figure 10 | Particulate pollutant contents by settling velocity category, as standardized with respect to content found in the untreated sample.
majority of these events, particulate pollutant sedi-
mentation velocities lie below the TSS sedimentation
velocity, with a V30_TSS/V30_pollutant ratio varying
between 1 and 5;

- particulate zinc and nitrogen feature a level of settle-
ability both systematically and significantly lower than
that of TSS. The V30_TSS/V30_pollutant ratio in this
instance varies for these two parameters between 2.5 and
10.5. A distinctly lower level of sedimentation than that
of TSS is thus to be expected for both zinc and nitrogen;

- particulate PAH behave completely differently from the
other pollutants studied by showing a settleability that in
most cases examined herein surpasses TSS settleability.
In five of the six samples analyzed, the V30 of PPAH
exceeds by a factor of 2 to 13 the V30 value associated
with TSS. Settling thus seems to provide a means of
treatment particularly well suited to the case of PAH.

Pollutant and micropollutant contents of particles
categorized by settling velocity

As a step towards better analyzing the pollutant distribution
by category of particle settling velocity, and thereby
improving understanding of the previously observed behav-
ior in terms of settling, we have calculated for each
settling velocity category the TSS pollutant content. These
contents were then standardized with respect to untreated
sample content, so as to homogenize the data. The results
derived from this standardization step are shown in
Figure 10 for organic matter, metals and nitrogen, and in
Figure 11 for PAH.

The assessment of contents by settling velocity category
makes it possible to identify the same pollutant groups as
previously cited.

- POC contents are stable and do not vary across settling
velocity categories. In contrast, the PCOD content of
particles regularly increases as settling velocity diminishes. The PCOD content of particles with a
settling velocity of less than 0.005 mm.s⁻¹ is roughly
three times greater than the content of particles with a
settling velocity above 0.8 mm.s⁻¹.

- For particulate copper and lead, a high variability in
standardized contents is recorded for all settling velocity
categories. A rising trend in content level with decreasing
settling velocities seems to prevail, although this trend is
not very pronounced.

- As regards particulate zinc, a distinct correlation appears
between zinc content and particle settling velocity. The
zinc content is even higher at low velocity values, with
the standardized median contents increasing from 0.6 for
Vₚ > 0.8 mm.s⁻¹ to 1.9 for Vₚ < 0.005 mm.s⁻¹.

- In the case of particulate nitrogen, particles settling at a
velocity of less than 0.005 mm.s⁻¹ are easily distinguis-
ushed from the 5 other particle categories, with
standardized contents on the order of 2.5. PTKN would
thus appear to be preferentially associated with particles
characterized by the lowest settling velocities.

- Lastly, concerning PPAH, the variability in standardized
contents within the same settling velocity category is very
high, which complicates the results interpretation step.
A content decrease can nonetheless be noted as settling
velocities decline, with sharply lower contents in the last
two settling velocity categories (i.e. Vₛ < 0.02 mm.s⁻¹).

CONCLUSION

Settling velocity is a key data for the design and the
management of WWF treatment devices. In the case of
storage-settling tanks, the knowledge of settling velocity
distributions of TSS and associated pollutants is necessary
to adjust the settling duration. In the case of on-line
stormwater settlers of simple geometry, the settling theory of discrete particles developed by Hazen (1904) and improved by Camp (1946) allows an easy appraisal of the removal efficiency. In these models, particle trapping is directly linked to the ratio of the settling velocity to the specific flowrate, i.e. flowrate divided by the horizontal settling surface (Li et al. 2007). For more complex settling tanks, two dimensional or three dimensional computational fluid dynamics modelling of water flow and particle transport will be needed (Milisic & Chebbo, 2005).

This article summarizes the primary results obtained during the OPUR2 research project regarding the sedimentation velocity of TSS and of various particulate pollutants found in combined sewer effluent during wet weather conditions. The measurement campaigns were run by implementing the VICAS and VICPOL protocols, both developed at the CEREVE research centre, as these two protocols offer reliable tools for evaluating pollutant settling velocities.

The TSS V50 settling velocities recorded during wet weather on the OPUR project sites lay on the order of 0.09 to 0.6 mm.s\(^{-1}\), and the V30 values span the range from 0.01 to 0.1 mm.s\(^{-1}\). These velocities exceed by a factor of 10 those derived from dry weather wastewaters (V50 = 0.009 to 0.065 mm.s\(^{-1}\)) and still remain higher than the values of pavement runoff, which suggests a contribution from particles with high settling velocities due to the erosion of organic deposits generated in combined sewer networks. These values however lie below the initial settling velocities measured by Chebbo: the V30 value of combined sewer effluent is generally quite a bit lower than 1 m.hr\(^{-1}\), i.e. 0.28 mm.s\(^{-1}\), which is still often set as the reference in France when designing settling facilities.

A variation in settling velocities has been observed between upstream sites (Marais) and downstream sites (Clichy, Coteaux, Clichy-downstream). The lower settling velocities experienced downstream could be explained not only by a greater proportion of wastewaters in the combined sewer effluent of downstream sites, but also by a disaggregation of particles caused by deposit erosion during upstream-downstream transport.

The results obtained for the settling velocities of particulate pollutants and micropollutants reveal that the efficiency of an eventual sedimentation treatment is indeed capable of varying as a function of the pollutant parameter under consideration: for POC, the effect is identical to that of TSS, while it would be less than that of TSS when considering PCOD, PCu and PPb, significantly less than that of TSS for PZn and PTKN, and on the other hand sharply higher than that of TSS for PPAH.

These last results were generated for a still limited number of rainfall events and just two measurement sites; they would need to be refined for a greater number of events over a large catchment basin. Furthermore, the distribution of pollutants by settling velocity category observed herein is specific to combined sewer effluent and may prove different within a strictly stormwater effluent.

According to the settling velocities measured over the OPUR2 study zone, the effectiveness of settling varies from one rainfall event to another, from one pollutant to another and from one site to another. The velocities taken into account in designing a settling structure should consequently be based on measurements conducted at the target site with a relatively high number of rainfall events and for all treated pollutants.

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