The erosion of organic solids in combined sewers

M. Ahyerre, C. Oms and G. Chebbo
Centre d’Enseignement et de Recherche sur l’Eau, la Ville et l’Environnement,
Ecole Nationale des Ponts et Chaussées, 6 et 8 Avenue Blaise Pascal,
Cité Descartes – Champs-sur-Marne, F - 77455 Marne-La-Vallee Cedex 2, France

Abstract Many studies undertaken on urban catchments show, thanks to indirect approaches, that the contribution of eroded sewer sediments to pollution of combined sewer overflows is significant and highly organic. An in situ study of the erosion of sewer sediments has been implemented to validate those results with a direct approach and to observe the processes of erosion.

Two experiments have been carried out on a 150 m length of combined sewer in “Le Marais” catchment in Paris, in order to determine the rate of erosion and the nature of the particles eroded by an injection of drinking water in the sewer system. Hydraulic and quality parameters have been measured in situ.

Those injections have shown that the rate of erosion is important (maximum rate of 146 g/s) at each stage of the injection, which has been conducted in three stages with a maximum flow of 370 m^3/h. The erosion does not only occur locally but happens along the entire length of the section even at low shear stresses (0.5 N/m^2). The eroded particles are highly organic (VS = 54–86%) and their loads in volatile solids, COD, BOD₅ decrease as the flow increases.

So, this work confirms, by direct measurements, that eroded sewer sediments are a significant source of organic matter that contribute to combined sewer overflow.

Keywords Combined sewer overflow; sewer sediments; erosion; organic matter; shear stress

Introduction
The pollution of combined sewer overflows is more significant than the pollution of storm sewer discharges (Bachoc, 1992; Chebbo, 1992; Saget, 1994). For example, the annual average concentrations of combined sewer overflows are one and a half more than those of storm sewers (Saget, 1994). This can be explained by the presence of two additional sources of pollution in the combined systems: wastewater produced during the rain events and stocks of pollutants present in the sediments of the combined systems.

However, the presence of wastewaters in combined systems does not explain the differences in the mass of pollution discharged during wet weather. Indeed, mass balances calculated by event or on an annual basis show that less than 20% of the suspended solids come from wastewater (Krejci et al., 1987; Chebbo 1992; Gromaire 1998).

Stocks of pollution in combined sewers thus play a significant role. At the annual scale, Chebbo (1992) has estimated the contribution of those stocks in suspended solids to be around 20% of the mass discharged. On the scale of a rain event, this contribution has been estimated for 4 rain events at 59% by Krejci et al. (1987) and between 30 and 44% by Bachoc (1992). Mass balances carried out for the experimental catchment of “Le Marais” in Paris (for 30 rain events, Gromaire (1998)) have shown that 30 to 80% of the mass of Suspended Solids, Volatile Solids, COD, BOD₅ at the outlet of the catchment, originate from in-sewer sources. The median mass eroded on “Le Marais” catchment (which has a surface area of 42 ha), ranges between 120 and 700 kg of suspended solids. Moreover, the mass eroded increases with the duration of the dry weather period before the rain event. In “Le Marais” sewer system, the particles eroded are highly organic (Volatile Solids/Suspended Solids=67%, COD/SS=1.1, BOD/SS=0.42). Within the time scale of a rain event, the particles are eroded for the duration of the rain event with a maximum rate of
erosion occurring during the most significant variations in flow. The organic content of the eroded particles is significant (VS content between 40 and 80%) during the entire rain event.

So, the combined sewer system is the main source of particulate and organic pollution during rain events.

The results presented above are based on mass balance calculations between the entry and the outlet of the system. They are therefore indirect. The objective of this article is to validate those results on the scale of a length of sewer, by a direct approach, and to answer these three questions:

- Is there a significant mass of particles eroded by high flows in combined sewer systems?
- What are the pollutant loads and the physical characteristics of the particles eroded?
- What are the main processes of erosion of sewer sediments?

The method used to cause the erosion relies upon in situ flushing experiments with drinking water on a sewer length of 150 m. The rates of erosion and the characteristics of the particles eroded during flushing events, are measured at the outlet from the length of sewer. The evolution of the hydraulic parameters of the flow are also measured (especially the shear stress). Then the nature and the mass of particles eroded along the length of sewer is determined and compared to the estimation made on the scale of the whole catchment.

Materials and methods

Characteristics of the section of sewer studied

The experiments have been carried out in the sewer system of the experimental catchment “Le Marais” in the center of Paris. This man entry sewer system includes three collectors with walkways. The length of collector chosen for the experiments is located at the upstream end of the collector “Vieille du Temple”: rectangular section, height 0.6 m, width 0.6 m, equivalent slope 0.04%. It has been chosen because it contained a significant amount of all types of sewer sediments. This section of the collectors is typical of the Parisian collectors with a gutter and one or two walkways. The length chosen to carry out the experiments of erosion is 150 m long and is drained into by 18 domestic branches and two small streets.

Method of flushing

The objective of the experiment was to measure the rate of erosion and the characteristics of the eroded particles, as a function of hydraulic parameters. We have chosen to use an artificial injection for two reasons. The first reason is that during a rain event, a significant amount of particles are eroded and transported at the surface of the catchment and finally enter the sewer system. In the sewer system, it is difficult to separate these particles, and it causes uncertainties in the estimation of the mass eroded. The second reason is a problem of security because the apparatus used to measure the hydraulic conditions and the samplers needed to be handled directly in the sewer system, and this is impossible during a rain event.

This experiment of erosion was carried out by means of a drinking water injection by way of water valves (fire hydrants) at the surface of the street. The water injected in the sewer system flows down a wall in order to limit the velocity of water when it is mixed with wastewaters so that there is no strong erosion locally. This injection was carried out at the upstream end of the length of sewer (see Figure 1).

During dry weather, the flow is around 30 to 40 m$^3$/h on this length of sewer. The maximum flow of injection used was 170 m$^3$/h per valve and two valves were used during the injections. So the maximum flow reached was 370 m$^3$/h with dry weather flow. In order to determine the significance of this flow compared to a real rain event, a hydraulic simulation has been carried out with MOUSE (Schlutter, 1998). It showed that the flow of injection at the outlet of the sewer length corresponds to the maximum flow of a little rain event (rain
event with a maximum intensity of 10 mm/h) and to the mean flow of very big rain events (maximum intensity of 237 mm/h).

Measurement of the shear stress

The shear stress was calculated using ADV (Acoustic Doppler Velocimeter, Sontek) measurements. The ADV emits a short and periodical acoustic signal, and three receivers measure the changes in frequency of the echo by Doppler effect. It allows the determination of the velocity of water along three perpendicular axes. The probe measures the velocity 11 cm under the transmitter in order not to disturb the flow under the point of acquisition. The volume used for measuring the velocity is 3 to 9 mm in length and 6 mm in diameter. We have worked at 25 Hz in order to obtain vectors that are representative of every component of the velocity and its variations in time.

Thanks to ADV measurement it is possible to calculate the shear stress. Indeed, the ADV measures the vector $V_x$, $V_y$ and $V_z$. Each component of these vectors, is the value measured at $t_1$, $t_2$, $t_3$ ... $t_n$, So, the shear stress is

$$\tau_{0} = -\rho u \nu$$

with $u' = V_x - \bar{V}_x$ and $v' = V_z - \bar{V}_z$.

The time step used for the determination of the mean values of the velocity is 10 s, and the measurements have been taken 1 cm above the base of the sewer.

Measurement of mass and characteristics of solids eroded

The rate of erosion during experiments was calculated by the difference between the total pollution load rate measured at the outlet of the length minus the estimated pollution load rate of wastewater. This calculation is made at each time step (3 minutes):

$$\phi_{ero}(t) = C(t) \cdot Q(t) - C_0(t) \cdot Q_0(t)$$

$\phi_{ero}(t)$: rate that particles are eroded (g/s)

$C(t)$: concentration measured at the outlet of the length of sewer during the experiments

$C_0(t)$: concentration measured at the outlet of the length of sewer during dry weather

$Q(t)$: flow measured at the outlet of the length of sewer during the experiments

$Q_0(t)$: flow measured at the outlet of the length of sewer during dry weather

The samples used to measure the concentrations are taken with an automatic sampler (Buhler PBMOS) in the middle of the flow. The sampler pumps 100 ml at one minute intervals, the samples are then gathered in sets of 3 in mixed samples, each corresponding to 3 minutes. The parameters of pollution analysed are: Suspended Solids, Volatile Solids, COD, BOD$_5$. The discharge has been measured by a water level measurement (piezometer PTX 1830) and a micro propeller (Ott C2).
Physicochemical analysis of waters

All the tests for suspended solids (SS), Volatile Solids (VS), BOD$_5$ concentrations are based on the standards AFNOR NF T 90-105, NF T 90-029 and NF T90-103. For the COD, the micro method or method of Hach was employed. The density of all the samples was measured by means of a pycnometer after oven drying at 105°C.

The measurement of the distribution of particles by class of settling velocities was undertaken by means of protocol CERGRENE 95 described in Lucas-Aiguier (1998). This protocol also allowed measurement of the volatile content by class of settling velocity.

Results and discussion

Dry weather pollution load rates

Dry weather concentration and flows have been measured on two occasions. The mean flow during dry weather at the outlet of the length of sewer was 42.1 m$^3$/h on the 22/07/98 between 9 and 12:30 pm and 39.7 m$^3$/h on the 18/11/98 at the same time. The pollution load rates during dry weather are very low and vary between 1–2.4 g/s in August and 1–1.9 g/s in November. The difference between the two periods of sampling is not significant.

So, we have chosen the dry weather pollution load rates measured in November (one week before the experiments of injection) to calculate the rate of erosion during the experiments. Moreover, the error introduced by the approximation of the dry weather pollution load rates is not significant compared to the values of the rates of erosion.

The mean particle loads during dry weather (18/11/98) are: volatile solids/SS = 84.7%; COD/SS = 1.189 g/g and BOD$_5$/SS = 0.377 g/g.

Rates of erosion and mass of eroded solids

Two experiments of erosion have been carried out. The variations of the flows injected in the two experiments are of the same order of magnitude. In both experiments, the injecting was done in three increments of flow.

For the experiment of the 26/11/98 (see Figure 2) the maximum rate of erosion at the first step is 146.5 g/s, 60 g/s at the second step and 62.5 g/s at the third one. The mass eroded at each step was 125.7 kg, 63.2 kg and 85.6 kg respectively.

For the experiment of the 02/12/98, the maximum rate of erosion at the first step was 84 g/s, 70 g/s at the second step and 25 g/s at the third one. The mass eroded at each step was

![Figure 2](https://iwaponline.com/wst/article-pdf/43/5/95/429685/95.pdf)

Figure 2 Total pollution load rates (g/s) and corresponding flows for two experiments (26/11/98 and 02/12/98)
59.8 kg, 43.5 kg and 32 kg respectively. So, as for the preceding experiment the most significant part of the mass was eroded during the first increment in flow.

The two experiments show the same results: at each flow increment, an important amount of particles are eroded and the most significant mass is eroded during the first flow increment. The only difference is the total mass eroded. This difference can be explained by the dry weather duration before each experiment. Indeed, the dry weather period before the experiment of the 26/11/98 was 3 weeks as opposed to only one week for the experiment of the 02/12/98.

The measurements of shear stress with the ADV (see Figure 3) show that the most significant mass is eroded with a low shear stress (less than 0.5 N/m²).
The process of erosion at each increment in shear stress can be divided into two distinct regions. First, there is a significant increase in erosion as a direct response to the increase in stress. Then, there is a stabilization of the rate of erosion. The rate of erosion during this stabilization is more significant for high shear stresses (see the experiment of 26/11/98).

In order to study the erosion of the particles and its evolution along the length of the sewer, during the experiment of 02/12/98, we used three samplers, placed at 50 m intervals. The first sampler was 50 m downstream of the point of injection, the second one was 100 m, and the third one was 150 m downstream.

### Table 1  Particle loads calculated for the particles eroded during the experiments

<table>
<thead>
<tr>
<th>Experiment 26/12/98</th>
<th>Particles eroded at the first step</th>
<th>Particles eroded at the second step</th>
<th>Particles eroded at the third step</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of samples</td>
<td>Volatile solids / dry solids (%)</td>
<td>DCO / dry solids (g/g)</td>
<td>DBOS / dry solids (g/g)</td>
</tr>
<tr>
<td>11</td>
<td>86</td>
<td>1.5</td>
<td>0.46</td>
</tr>
<tr>
<td>13</td>
<td>79</td>
<td>1.2</td>
<td>0.39</td>
</tr>
<tr>
<td>20</td>
<td>70</td>
<td>1.1</td>
<td>0.31</td>
</tr>
</tbody>
</table>

### Table 2  Particle loads in volatile solids (%) in the particles eroded by class of settling speed (02/12/98)

<table>
<thead>
<tr>
<th>Particles eroded at the first increment</th>
<th>Particles eroded at the second increment</th>
<th>Particles eroded at the third increment</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2 cm/s &lt; - &lt; 0.5 cm/s</td>
<td>80</td>
<td>68</td>
</tr>
<tr>
<td>0.02 cm/s &lt; - &lt; 0.2 cm/s</td>
<td>81</td>
<td>64</td>
</tr>
<tr>
<td>0.002 cm/s &lt; - &lt; 0.02 cm/s</td>
<td>75</td>
<td>64</td>
</tr>
<tr>
<td>&lt; - 0.002 cm/s</td>
<td>83</td>
<td>78</td>
</tr>
</tbody>
</table>

### Table 3  Nature of particles eroded (for 30 rain events) at the scale of the catchment estimated by mass balances (Gromaire, 1998) and nature of the particles eroded during the experiments

<table>
<thead>
<tr>
<th>Pollutant loads of particles eroded during rain events (Gromaire, 1998)</th>
<th>Mean pollutant load of particles eroded during the experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volatile solids/dry solids solids (%)</td>
<td>1st decile</td>
</tr>
<tr>
<td>COD / dry solids (g/g)</td>
<td>0.77</td>
</tr>
<tr>
<td>BOD5 / dry solids (g/g)</td>
<td>0.29</td>
</tr>
<tr>
<td>COD / BOD5 (g/g)</td>
<td>1.1</td>
</tr>
</tbody>
</table>

### Table 4  Mass of particles eroded by 30 rain events and mass eroded during the flushing experiments on the sewer length

<table>
<thead>
<tr>
<th>Mass eroded (kg) at the scale of the catchment (Gromaire, 1998)</th>
<th>Mass eroded (kg) during the experiments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry solids</td>
<td>1st decile</td>
</tr>
<tr>
<td>Volatile solids</td>
<td>124</td>
</tr>
<tr>
<td>COD</td>
<td>110</td>
</tr>
<tr>
<td>BOD5</td>
<td>184</td>
</tr>
<tr>
<td>COD / BOD5</td>
<td>65</td>
</tr>
</tbody>
</table>

The process of erosion at each increment in shear stress can be divided into two distinct regions. First, there is a significant increase in erosion as a direct response to the increase in stress. Then, there is a stabilization of the rate of erosion. The rate of erosion during this stabilization is more significant for high shear stresses (see the experiment of 26/11/98).
100 m downstream of the point of injection and the third one was at the outlet of the length of sewer (150 m downstream of the point of injection). The mass eroded for each flow increment has been calculated at every sampling point thanks to the measurements of flows and concentrations made at each point during dry weather and during the experiment.

For the first flow increment (see Figure 4), the mass eroded was 25.3 kg for the upstream sampling point, 46 kg for the intermediate point and 59.8 kg at the outlet. For the second increment, the mass eroded was 23.1 kg for the upstream sampling point, 25.6 kg for the intermediate point and 43.5 kg at the outlet. For the third increment, the mass eroded was 12.6 kg for the upstream sampling point, 18.1 kg for the intermediate and 32 kg at the outlet.

So, the erosion of the particles is not local, it occurs over the entire length of this sewer, it is not however very uniform.

Characteristics of the eroded particles
The evolution with time of the loads of volatile solids in the eroded particles during the two experiments have been calculated precisely. At each time step, the rate of erosion of volatile solids eroded has been calculated, then the loads of volatile solids (Volatile mass of particles eroded/dry mass of particles eroded) are calculated. The same calculations have been done for the other parameters (COD, BOD₅) using mixed samples corresponding to durations that range from 30 minutes to one hour (see Table 1).

It is very clear that the eroded particles become less and less organic as the flow increases. At the beginning of the erosion, the loads of volatile solids are close to dry weather flow values and at each increment in injected flow they decrease until reaching the lowest value of 54% during the last increment in flow in the experiment of 02/12/98. For the other parameters, the conclusion is the same: pollutants load decreases as the flow increases.

Moreover, Figure 4 shows that the nature of the eroded particles does not vary with displacement. Nor does the nature of the particles with the settling velocities (see Table 2). This means that all the types of eroded particles have the same loads in volatile solids (except for the particles of very low settling velocity).

The particles eroded at the beginning of each flow increment have very high settling velocities ($v_{50} = 0.1$ cm/s) compared to dry weather flow particles ($v_{50} = 0.009$ cm/s). The particles eroded at each step of erosion are also denser. For instance, the density of the particles from the first flow increment (26/11/98) was 1316 kg/m³, 1447 kg/m³ for the second and 1538 kg/m³ for the third one. Those densities are high compared to the density of the particles found during times of dry weather that have been measured (1309 kg/m³).

Comparison of the particles eroded during the experiments with the particles eroded during rain events of a suitable scale for the catchment
The pollutant loads of the particles eroded during the experiments are of the same order of magnitude as the loads calculated for real rain events, especially for volatile solids. The only difference concerns COD which was greater during the experiments, but this difference is not significant (Table 3).

This result means that the particles eroded during the experiments are the same as the particles eroded during rain events and that those particles are very organic.

The mass of dry solids eroded during the experiments is significant (see Table 4). This confirms that the sewer system is a major source of organic particles. The mass eroded from 150 m of sewer is very high compared to the mass eroded for a median rain event on the whole sewer system. Indeed, the sewer length in “Le Marais” sewer system is 7.6 km.

This difference in the mass eroded on the scale of the catchment or on the scale of the sewer section can be explained by a hypothesis. A cartography of the deposits in this sewer system has shown that 90% of the mass of sewer sediments (type A sediments according to
the classification of Crabtree (1989)) are located in a length of 1220 m at the upstream ends of the main sewers. The sewer length chosen for these experiments is at the upstream end of the most clogged sewer. Of the 1220 m of sewer, where these deposits lie, the majority of the erodible particles could be concentrated within a few hundred of metres. Those locations correspond to places where flow velocity is very low, allowing organic particles to settle.

Conclusions

The experiments of injections of clean water into the sewer system have confirmed the results established on “Le Marais” catchment:

• the mass eroded in the sewer system by an increase of flow is significant,
• the particles eroded in the sewer system are highly organic,
• the erosion occurs at each increase in shear stress.

In order to improve our knowledge of the processes of erosion and to have more efficient storm water quality models, we think that it is necessary to focus on the identification of the origin of organic particles that are eroded during rain events. This source could be composed either of Type A sediments (Crabtree, 1989), biofilms (Krejci et al., 1987) or of solids located at water bed interface (“dense undercurrent” (Verbank, 1995), “near bed solids” (Arthur, 1996), “fluid sediments” (Ashley et al., 1994)).

An investigation is currently being carried out at CEREVE in order to characterise the different types of sediments along the sewer length. This will allow us to compare the masses and the characteristics of the solids eroded in the experiments to the masses and characteristics of the stocks of sediments, in order to identify the source of organic particles in combined sewers.

Acknowledgements

The authors would like to thank both the Agence de l’eau Seine Normandie and the Ville de Paris for financial support during this research project. Also Owen Francis for assisting with the translation.

References