

## Characterisation of retention tank water quality: particle settling velocity distribution and retention time

Thibaud Maruéjols, Peter A. Vanrolleghem, Geneviève Pelletier and Paul Lessard

### ABSTRACT

Retention tanks (RTs) are commonly used to reduce combined sewer overflows, management of which is an important way of reducing the impacts of urban development on receiving waters. However, overflow characteristics and the processes affecting them are not yet fully understood. In a context of integrated urban wastewater systems, the management of RTs is mainly done to satisfy hydraulic constraints even if the idea behind such structures is to limit the discharge of pollutants to the environment. This study reports new insights in the settling processes and the pollutant behaviour occurring in an off-line RT. The authors first focus on the total suspended solids (TSS) and the total chemical oxygen demand (COD<sub>t</sub>) dynamics at the inlet and the outlet of a RT. Secondly, they focus on the possible relationship between the variation of the particle settling velocity distribution of particles and the TSS concentration dynamics. Finally, analyses of the TSS and COD<sub>t</sub> concentration evolution during tank emptying give information on the interaction between wastewater retention time and the settling performance.

**Key words** | combined sewer overflow, settling efficiency, urban wastewater management, wastewater quality

**Thibaud Maruéjols** (corresponding author)  
**Peter A. Vanrolleghem**  
**Geneviève Pelletier**  
**Paul Lessard**  
Département de génie civil et de génie des eaux,  
Université Laval,  
Pavillon Adrien-Pouliot,  
1065 Av. de la médecine,  
Québec, Qc,  
G1V 06A,  
Canada  
E-mail: [Thibaud.Maruejols.1@ulaval.ca](mailto:Thibaud.Maruejols.1@ulaval.ca)

### INTRODUCTION

In many cities in the world, the drainage network is mainly composed of combined sewers and is thus prone to combined sewer overflows (CSOs). With the increased imperviousness in urban areas, cities have to deal with increased stormwater volumes transported by the sewers. Stormwater combines with dry weather flow to produce water with a quality comparable to that of dry weather flow in terms of total suspended solids (TSS), chemical oxygen demand (COD) and many other relevant pollutants such as biochemical oxygen demand (BOD), nitrogen, pathogens or micropollutants (Howard *et al.* 1986; Lessard 1989; Gromaire-Mertz 1998; Gromaire-Mertz *et al.* 1999; Rechenburg *et al.* 2006). Building retention tanks (RTs) is generally the solution adopted to reduce CSOs. In 1985, Lindholm questioned whether RTs had an overall positive or negative environmental impact on the receiving water body. Indeed, retention of stormwater in sewers reduces

CSOs, but it also leads to various problems when the water is subsequently sent to the wastewater treatment plant (WWTP). As per Ashley *et al.* (2002), RT emptying can lead to late flushes or lengthy periods of high hydraulic flow entering the WWTP, resulting in a loss of treatment efficiency. The increasing use of pumps and sluice gates for emptying such tanks allows for better management. However, the phenomena occurring in the tanks are still poorly understood. Understanding particle behaviour in RTs in the context of integrated management, i.e. management that considers the interaction between sewer, WWTP and rivers, is a key element to control the impact of their emptying on the WWTP (Ashley *et al.* 2002). Previous work by Maruejols *et al.* (2011) characterised the potential impact of RT emptying on primary clarification, the first major unit process of a WWTP. The paper compares particle settling velocity distribution (PSVD) profiles of samples

collected during the emptying period to analyses carried out at the inlet and the outlet of a primary clarifier. The largest volume fraction emptied from the RT transports particles with a PSVD similar to what is observed at the outlet of a primary clarifier whereas the initial and final fraction of the stored combined sewage have much more concentrated particles and with faster settling velocities. That knowledge can be used to adapt the operating schemes that are currently set up to manage the flow to the WWTP in view of improving treatment efficiency. Indeed, the volume of the middle phase could bypass the clarifier avoiding its hydraulic disturbance. Furthermore, flow management at the WWTP could take into account these phases in view of reducing the amount of particles with high settling velocity ( $V_s$ ) that could enter the secondary treatment.

Whereas the insights in the quality of combined sewer wastewaters benefitted from the collection of large data sets over the years, the water quality and pollutant behaviour in storage structures such as RTs remain less known. Even if some characterisation studies have been carried out (Brechenmacher *et al.* 1992; Aires *et al.* 2003; Boxall *et al.* 2007), their number is not sufficient to allow in depth comparison of the different sampling campaigns. Very few data are available in the literature reporting the PSVD in RTs. Some studies were carried out (Michelbach & Weiß 1996; Maruejouis *et al.* 2011) showing wide ranges of PSVD. Michelbach & Weiß (1996) stated and found in 19 events that 50% of the settleable solids had a median  $V_s < 7.56$  m/h at the inlet of a clarifier-type CSO tank. As this study was performed on a clarifier-type CSO tank, the settled particles were not released through the outflow. They also noted a correlation between the flow variation and the PSVD, i.e. an increase of the flow at the inlet corresponds to an increase of the average particle  $V_s$ . However, no clear correlation could be deduced. For example, at the tank inlet, the authors showed that for a flow of 28,800 m<sup>3</sup>/h, the average  $V_s$  can vary from 5.4 to 23.4 m/h, and are around 10.8 m/h for a flow of 45,000 m<sup>3</sup>/h. Thus,  $V_s$  can be low even for high flows. This can be explained by the fact that the calculations were done using averages of concentration and flow data rather than individual results from grab samples. Furthermore, the correlation between flow and TSS can be distorted since it highly depends on the pollutant accumulation on the catchment. That is to

say, a same flow will not be able to transport the same particles if the accumulation is different. For example, in the case of two consecutive events with similar flows, the first storm will wash-off all mobilisable particles that will therefore not be present for the subsequent storm.

The present work aims at highlighting PSVD variations during filling and emptying a RT. In this study, the PSVD is not correlated to the flow at the inlet, but to the TSS concentration. Characterisation of the TSS variation at the outlet of the RT is also used to find reproducible behaviours leading to a better understanding of the settling processes. Treatment efficiency with respect to retention time in the tank is then analysed.

The objectives of the paper are to present:

- the characterisation of the wastewater quality during filling and emptying in terms of TSS and total COD (COD<sub>t</sub>);
- the characterisation of the changes in the PSVD during those periods and its correlation with the TSS concentration; and
- the assessment of the effect of retention time on the settling efficiency.

---

## MATERIAL AND METHODS

### Case study

The off-line RT in this study is located in a Quebec City (Canada) urban catchment with a total area of 1.46 km<sup>2</sup> and an average imperviousness of 51%. The land use is mainly residential. The concentration time is about 26 minutes and the total population is estimated to be around 5,200 habitants. The RT has a capacity of 7,580 m<sup>3</sup> (25 m<sup>3</sup>/ha<sub>imp</sub>) and was designed for four overflows per summer period (May 15th to September 15th). The tank is emptied by five pumps located in a pumping well. Detailed characteristics concerning the urban catchment and the RT operation are provided in Maruejouis *et al.* (2011).

### Sampling campaigns

The data were collected during two sampling campaigns in the summers of 2009 and 2010. Sampling consisted of

collecting water at the inlet and outlet of the tank. The outlet means the return pipe to the WWTP. Several samples were taken with a variable time interval (2 minutes to 2 h) during each event for both the inlet and outlet. This variable interval allows limiting the number of samples to analyse without missing periods of high variation in concentrations. These time intervals were set in order to observe the pollutant concentration dynamics during emptying. The samples were then analysed at Université Laval's Environmental Laboratory, mainly for TSS, COD<sub>t</sub> and PSVD (Vs, see below).

The influent sampling point was located downstream of the weir directing wastewater to the RT. Grab samples were collected with an automatic sampler (SIGMA 900max) including 24 1-L bottles. This sampler is connected to a float switch (FLYGT ENM-10) which controls the sampler activation when water flows over the weir. The outlet sampler is located just after the pumps and is equipped with the same sampling material.

### Laboratory analyses

Once the samples were collected, they were either analysed immediately or stored in a cold chamber at 4 °C to be analysed within 24 h. Conservation tests were conducted in order to assess the phenomena of flocculation that may have an impact on the Vs characterisation. The tests showed that there was no significant impact on the measurements if analyses were performed within 24 h.

TSS analyses were performed according to Standard Methods (APHA *et al.* 2012). The COD<sub>t</sub> was analysed with the Hach closed-reflux method (method Hach 8000) after grinding and homogenisation of the samples. Measurements of PSVD were carried out using the ViCAs protocol (Chebbo & Gromaire 2009) both on composite and grab samples. The ViCAs protocol consists of inserting a wastewater sample in a vertical Plexiglas column (diameter 7 cm, height 60 cm). The wastewater sample is quickly sucked up with a pump (around 2 seconds for 2.5 L) to avoid settling during the filling of the column. The mass of settled particles is collected at the bottom of the column at various time steps during 24 h. A simple numerical application calculates the Vs corresponding to a certain particle mass, making a fit between the model and the accumulated mass with regard to time.

### Event mean concentration (EMC)

To calculate the mass fluxes and the EMC, pollutant concentrations measured *in situ* have to be interpolated. Indeed, flow data are available for a time step of 1 minute, whereas the concentration data for an event include only eight to 10 sampling points. A simple linear interpolation method is used here (see Maruejols *et al.* (2011) for details).

The EMC (g/m<sup>3</sup>) is equal to the sum of the pollutant mass  $M_i$  (g) of an event divided by the total water volume  $V_i$  (m<sup>3</sup>) at time  $t$ . It gives a global average concentration for an event weighted by the flow variation. As expressed by Equation (1), this value thus gives information on the pollutant load for an event and allows for comparison between events:

$$\text{EMC} = \frac{\sum_{i=1}^N M_i}{\sum_{i=1}^N V_i} = \frac{\sum_{i=1}^N Q_c \cdot C_i}{\sum_{i=1}^N V_i} \quad (1)$$

The loads  $\hat{L}$  later shown are calculated similarly, following Equation (2):

$$\hat{L} = \sum_{i=1}^N M_i = \sum_{i=1}^N Q_c \cdot C_i \quad (2)$$

At the outlet, level sensors lit-008 and lit-009 are respectively located at 7 and 15 m from the pumps inside the tank and are assumed to give a good estimate of the volume variation and, thus, of the flow leaving the tank. These flow rates were used for the outlet EMC calculation. Concerning flow rate at the inlet, it was necessary to correct collected data because the time integration of the flow measured over the weir seemed to lead to errors of up to 300% on the volume observed in the tank. The flow calculation (Equation (3)) is based on a single water level measurement which is not adapted to the case study since it is well-known that the water height changes along the weir. The corrected flow  $Q_c$  (m<sup>3</sup>/h) is calculated by multiplying the flow measurements obtained at the weir, thanks to a water level sensor, by a correction factor (Equation (4)). The correction factor  $\alpha$  was found by fitting the volume having passed over the weir to the volume measured in the tank (after the weir):

$$Q = C_d \cdot B \cdot \sqrt[3]{h_e - h_d} \quad (3)$$

where  $Q$  = calculated flow rate ( $\text{m}^3/\text{s}$ );  $C_d$  = weir coefficient ( $C_d = 2.385$ );  $B$  = weir width ( $B = 7$  m);  $h_e$  = measured water level (m); and  $h_d$  = weir height (m):

$$Q_c = \alpha \cdot Q \quad (4)$$

where  $Q_c$  = corrected flow rate ( $\text{m}^3/\text{s}$ ); and  $\alpha$  = correction factor.

This approach has the advantage of maintaining the flow dynamics observed over the weir, instead of using the volume variation in the tank where the flow dynamics are buffered by a 200 m pipe located between the weir and the tank.

## RESULTS AND DISCUSSION

### Rainfall characteristics

During the summer campaigns of 2009 and 2010, 18 rain events with a wide range of characteristics were sampled. A 'rain event' is defined by the instant at which the first drop of water spills over the weir and the tank is empty. The event characteristics have already been published in Maruejols *et al.* (2011).

### Water quality

Water quality from the measurement campaign at the inlet and the outlet of the off-line RT are presented in this section.

First, EMC calculations for 11 events are presented to estimate the pollutant load ranges. The EMC have only been calculated for events which were adequately sampled. That is to say, since the pollutant concentrations vary strongly in quite a short time (up to a few hundreds of  $\text{g}/\text{m}^3$  over 10 minutes), seven events were sampled in which some important points of the pollutant dynamics were missed. Thus, the EMCs were not calculated for these events. Then, CODt and TSS pollutographs are shown. Finally, results regarding the PSVD of the particles associated with the pollutographs highlight pollutant behaviours and, more specifically, the flux of the particles.

### Event mean concentration

Table 1 reports literature results of various combined sewer water quality characterisation campaigns carried out in various places under wet weather conditions. It also presents statistics on the different EMC calculations to give an idea of the observed range – the minimum, maximum and average. The widest ranges were observed by Suarez & Puertas (2005) in Spain, with TSS EMC values between 61 and 1,379  $\text{g}/\text{m}^3$  and CODt EMC values between 128 and 1,472  $\text{gO}_2/\text{m}^3$ . Obviously, TSS and COD concentrations in CSOs depend heavily on antecedent dry periods and intensities of recent rain events, which are both related to climate, land use and catchment size. Ranges of EMCs reported in this work agree with those found in the literature

**Table 1** | TSS and CODt EMC values and number of sampled events used for calculations found in the literature compared with the current results. These case studies are all located on residential areas

|                                   | TSS EMC ( $\text{g}/\text{m}^3$ ) |              |            | CODt EMC ( $\text{gO}_2/\text{m}^3$ ) |            |            | Number of events |
|-----------------------------------|-----------------------------------|--------------|------------|---------------------------------------|------------|------------|------------------|
|                                   | Min.                              | Max.         | Average    | Min.                                  | Max.       | Average    |                  |
| Kafi <i>et al.</i> (2008)         | 121                               | 519          | 275        | 190                                   | 737        | 418        | 27               |
| Suarez & Puertas (2005)           | 61                                | 1,379        | 618        | 128                                   | 1,472      | 667        | 46               |
| Shu (2004)                        | 273                               | 551          | 370        | 264                                   | 481        | 367        | –                |
| Diaz-Fierros <i>et al.</i> (2002) | 160                               | 411          | 282        | 134                                   | 540        | 329        | 7                |
| Sztruhár <i>et al.</i> (2002)     | –                                 | –            | 430        | –                                     | –          | 445        | 8                |
| Chebbo <i>et al.</i> (2001)       | 120                               | 530          | 215        | 200                                   | 645        | 330        | 67               |
| Ellis (1991)                      | 176                               | 647          | 425        | 250                                   | 530        | 380        | –                |
| <b>This study</b>                 | <b>40</b>                         | <b>1,398</b> | <b>402</b> | <b>70</b>                             | <b>369</b> | <b>155</b> | <b>11</b>        |

– = not provided.

for TSS, whereas the CODt EMC average is lower than that found in the literature (Table 1). Most of the cited studies were carried out in Europe, except for Shu (2004) which was in the USA. Thus, the CODt/TSS ratio is higher in Europe. This difference is difficult to explain. However, results obtained by Lessard & Lavallée (1985) on the same combined sewer catchment of Quebec City are consistent with those from this study. One can imagine this difference to be due to the fact that dry weather wastewaters are more diluted in North America compared with Europe. As a result, CODt is lower in North America.

TSS values are comprised of between 386 and 49,936 g/m<sup>3</sup> for the outlet and between 122 and 2,451 g/m<sup>3</sup> for the inlet (Table 2). This observation is correlated to the operation of the RT and the dynamics of the pollutants (detailed below). Indeed, at the outlet, the variations are more important and occur over a shorter period of time. The maximum value during the emptying of the tank for the July 13, 2010, July 16, 2010 and August 3, 2010 events are abnormally high (respectively 6,124, 49,936 and 21,503 g/m<sup>3</sup>). That period corresponds to roadwork that took place on the catchment, consisting of digging under the road to resurface it, mobilising a large quantity of inorganic particles (hence the lower CODt/TSS ratio).

## Filling period

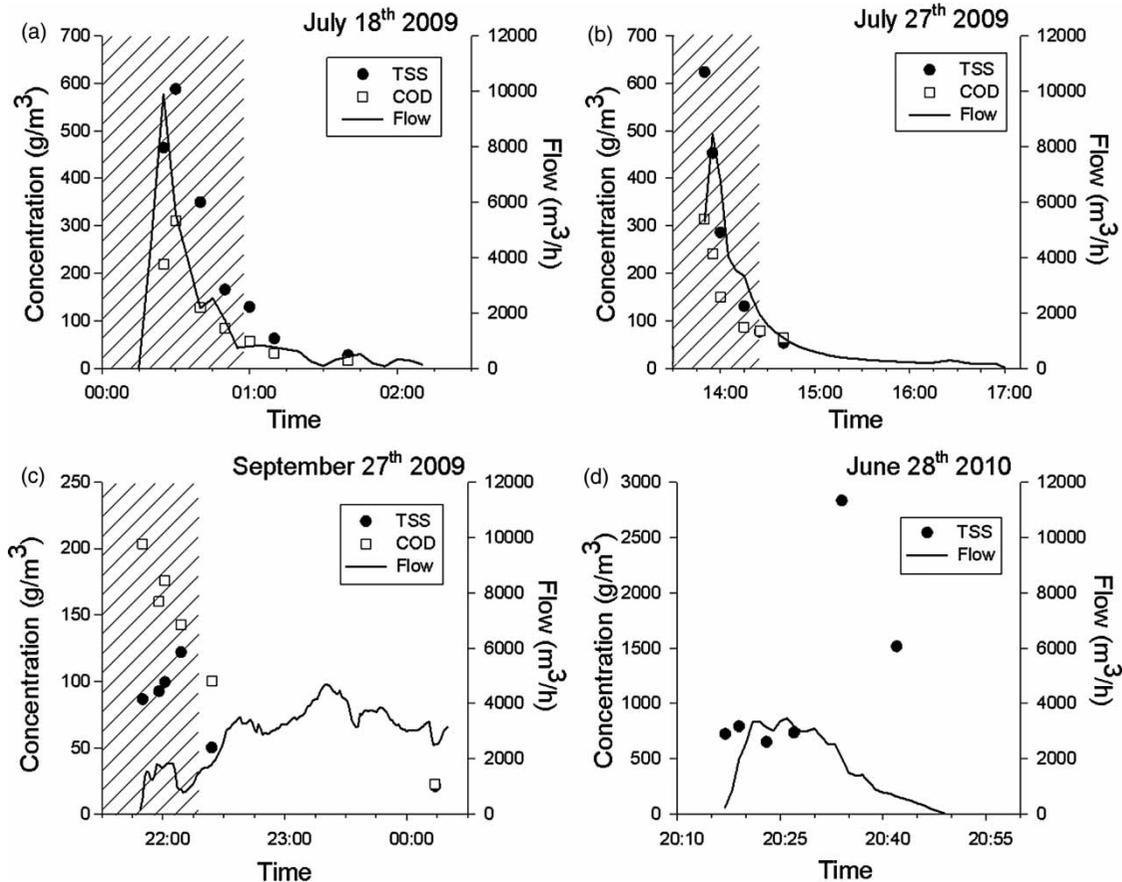
### Pollutographs

Four complete events (where both the filling and the emptying periods were entirely sampled) are presented herein (Figure 1). For each event, TSS and CODt concentrations are represented by symbols and flow is plotted as lines. For Figure 1(d), only the TSS is reported. Calomino et al. (2004) reported TSS concentrations between 25 and 4,480 g/m<sup>3</sup> and CODt concentrations between 45 and 1,380 gO<sub>2</sub>/m<sup>3</sup> in combined sewers. In the present paper, TSS concentrations are between 40 and 2,830 g/m<sup>3</sup>, and CODt between 30 and 670 gO<sub>2</sub>/m<sup>3</sup> (Table 2). These concentrations agree with the literature. Flow reaches a maximum of 10,000 m<sup>3</sup>/h during the July 18, 2009 event. For the three first events, the peak concentrations within the first minutes of filling correspond to the 'first flush' phenomenon (Bertrand-Krajewski et al. 1998; Deletic 1998). This load corresponds to the mass of pollutants which is washed-off from the catchment plus what is resuspended in the sewer system. Subsequently, the concentrations reach a threshold which corresponds to the dry weather water quality diluted by runoff water. Thus, a filling period pollutograph can be typically split in two phases

**Table 2** | Inlet and outlet EMC values and maximum concentrations for different events in terms of TSS and CODt

|           | Inlet<br>TSS            |                                      | CODt                                   |   | Outlet<br>TSS           |                                      | CODt                                   |   |
|-----------|-------------------------|--------------------------------------|--|---|-------------------------|--------------------------------------|--|---|
|           | EMC (g/m <sup>3</sup> ) | C <sub>max</sub> (g/m <sup>3</sup> ) | EMC (gO <sub>2</sub> /m <sup>3</sup> ) | C <sub>max</sub> (gO <sub>2</sub> /m <sup>3</sup> ) | EMC (g/m <sup>3</sup> ) | C <sub>max</sub> (g/m <sup>3</sup> ) | EMC (gO <sub>2</sub> /m <sup>3</sup> ) | C <sub>max</sub> (gO <sub>2</sub> /m <sup>3</sup> ) |
| 18/7/2009 | 319                     | 588                                  | 152                                    | 309   | –                       | –                                    | –                                      | –   |
| 27/7/2009 | 179                     | 624                                  | 107                                    | 315   | 185                     | 1,920                                | 204                                    | 1,408   |
| 21/8/2009 | 103                     | 192                                  | 94                                     | 238   | 137                     | 844                                  | 117                                    | 627   |
| 27/9/2009 | 40                      | 122                                  | 68                                     | 204   | 104                     | 998                                  | –                                      | –   |
| 28/6/2010 | 1,398                   | 2,832                                | –                                      | –   | 1,337                   | 2,044                                | –                                      | –   |
| 9/7/2010  | 1,282                   | 2,451                                | 369                                    | 672   | 204                     | 386                                  | –                                      | –   |
| 13/7/2010 | 312                     | 499                                  | 291                                    | 599   | 210                     | 6,124                                | 127                                    | 1,831   |
| 16/7/2010 | 274                     | 792                                  | –                                      | –   | 1,167                   | 49,936                               | –                                      | –   |
| 3/8/2010  | 100                     | 255                                  | 70                                     | 396   | 217                     | 21,503                               | 134                                    | 4,452   |
| 6/9/2010  | 153                     | 267                                  | 138                                    | 311   | –                       | –                                    | –                                      | –   |
| 13/9/2010 | 270                     | 431                                  | 105                                    | 363   | –                       | –                                    | –                                      | –   |

– = non-analysed.



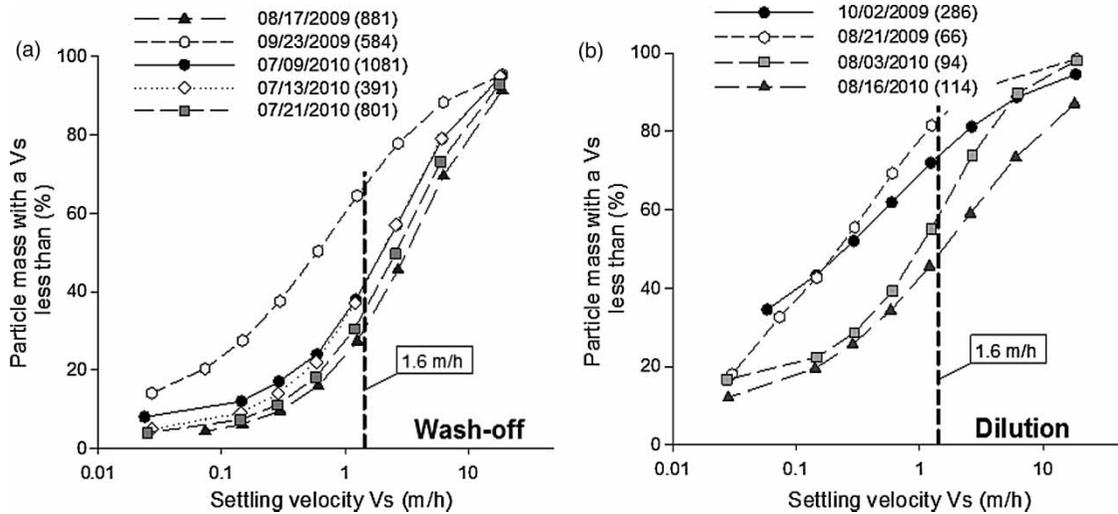
**Figure 1** | Event pollutographs at the tank inlet for the events of: (a) July 27, 2009; (b) July 18, 2009; (c) September 27, 2009; and (d) June 28, 2010. Hatched zones represent the volume fraction identified as the first flush effect (TSS > 100 g/m<sup>3</sup>).

called the ‘wash-off’ (hatched) and the ‘dilution’ (non-hatched) periods (Figure 1). Only the June 28, 2010 event does not follow this typical pollutant dynamics. However, this divergence can be explained by roadwork carried out on the urban catchment, bringing large quantities of sand with particularly high Vs. Indeed, the maximum concentrations are abnormally high, around 3,000 g/m<sup>3</sup> compared with the others which remain below 1,000 g/m<sup>3</sup>.

### Particle settling velocity distribution

Previously, Maruejols *et al.* (2011) demonstrated the possible correlation between PSVD and TSS concentration. Figures 2(a) and (b) present ViCAs curves performed on RT inlet samples for the ‘wash-off’ and the ‘dilution’ periods respectively (refer to Figure 1). TSS concentrations for each sample are written in parentheses in the legend (in g/m<sup>3</sup>).

As seen in the previous paragraph, differences can be found in TSS concentrations, i.e. for the ‘wash-off’ period, the overall TSS average for all samples is equal to 747 g/m<sup>3</sup>, while it is equal to 140 g/m<sup>3</sup> for the ‘dilution’ phase. Comparison of these two figures underlines that a bigger fraction of the particle mass settles faster within the ‘wash-off’ phase than within the ‘dilution’ phase. Michelbach & Weiß (1996) revealed a median Vs (50% of the total mass) of 7.56 m/h at the inlet of their RT with a clarifier, while in this work, the median Vs is lower at around 3 m/h within the ‘wash-off’ phase and around 0.9 m/h within the ‘dilution’ phase. Focussing on the ‘wash-off’, one can note that the particle mass with a Vs less than 1.6 m/h mainly lies between 30 and 40%, except for the September 23, 2009 event (65%) where the spilling over the weir to the tank was following several other spills. The value of 1.6 m/h was chosen as a reference because it is a



**Figure 2** | VICAs curves from various events collected within: (a) the 'wash-off'; and (b) the 'dilution' period. In parenthesis, the TSS concentrations for each sample in  $\text{g}/\text{m}^3$ . The grey colour gradient reflects the TSS concentrations (dark = high concentrations).

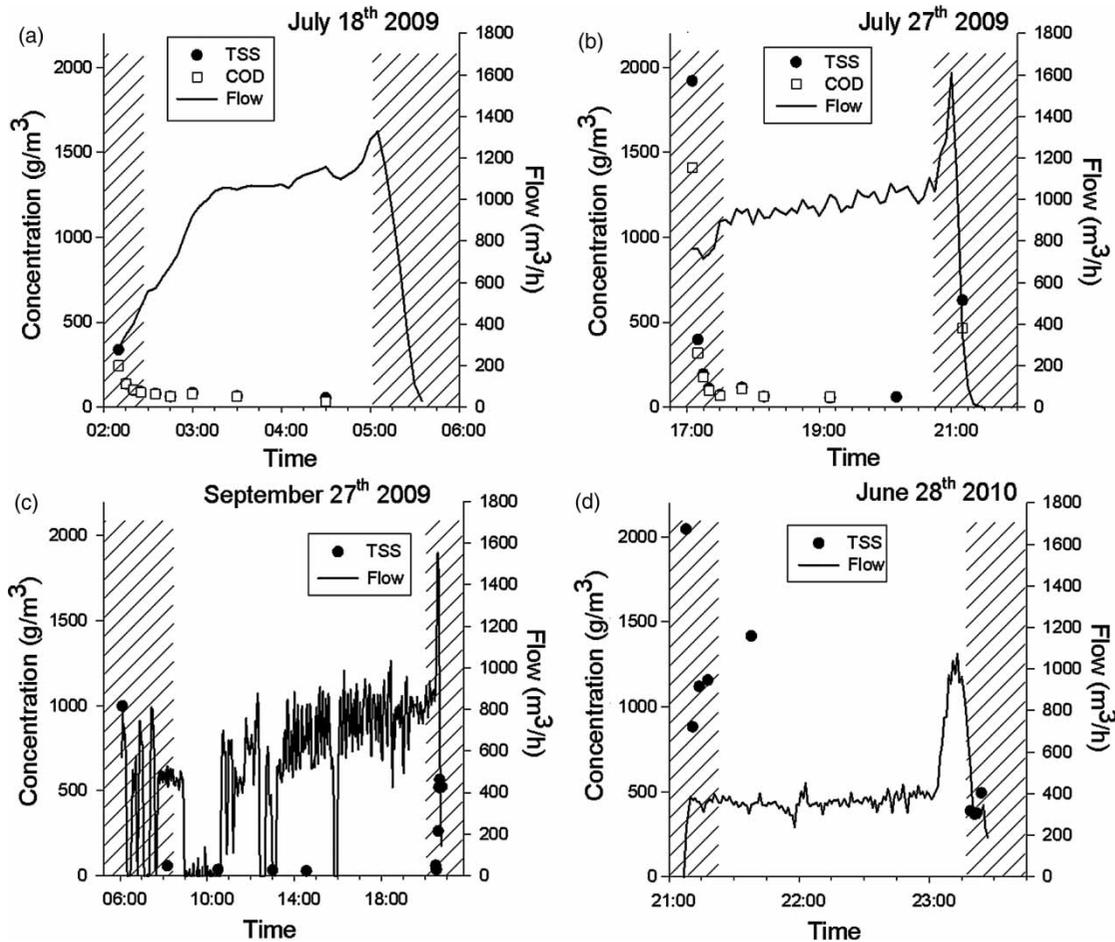
design criterion for primary clarifiers corresponding to the  $V_s$  of particles to be removed (Metcalf & Eddy 2003). For the September 23, 2009 event, the sediment had already been washed-off when the samples were collected since a first rainfall had previously washed-off a fraction of those sediments. This explains why the PSVD is located clearly above the other PSVDs of the wash-off period. The particle mass with a  $V_s$  less than 1.6 m/h remains between 40 and 80% for the 'dilution' phase. August 2010 was marked by roadwork on the catchment and an increase in TSS concentrations. Under 'normal' conditions, these fractions (mass of particles with a  $V_s$  less than 1.6 m/h) are usually higher than 60%.

## Emptying period

### Pollutographs and phase characteristics

TSS and  $\text{COD}_t$  concentrations vary highly during the emptying period. For example, the events in Figure 3 show concentrations between 45 and  $2,100 \text{ g}/\text{m}^3$  for TSS and 30 and  $1,450 \text{ gO}_2/\text{m}^3$  for  $\text{COD}_t$ . The flow is rather constant during the whole emptying until the end where a flow increase is programmed to extract a maximum of particles before the pumps stop. The maximum flow never exceeds  $1,600 \text{ m}^3/\text{h}$ .

Reproducible dynamics are observed over all events. Indeed, an emptying pollutograph can be split in three phases including two pollutant concentration peaks during the 'initial' and the 'final' phases (hatched on Figure 3), and a low constant concentration period during the 'middle' phase (non-hatched on Figure 3). Analysis of mass balances and PSVDs led the authors to strongly consider that the matter contained in the 'initial' peak was due to particles remaining in the pumping well after the end of the emptying of the previous event plus settled particles from the current event. The matter contained in the 'final' peak corresponds to particles extracted by both the increase of the pumped flow and the small water volume remaining, increasing the mixing intensity and thus resuspension. Finally, particles from the 'middle' phase are the suspended particles which did not settle during storage. These phenomena helped to structure the RT model published in Maruéjols *et al.* (2012). The duration of the 'initial' phase is around 15 minutes and is 10 minutes for the 'final' phase, while the duration of the 'middle' phase is variable. Only the July 18, 2009 event graph does not show the final pollutant concentration peak. As mentioned previously, since this event was one of the first the authors sampled, that last peak was not yet well-known. Thus, no sample was taken at the end of emptying. The quick variations observed in the flow rate for the September 27, 2009 event are due to a malfunctioning of the pumps.



**Figure 3** | Event pollutographs at the tank outlet for the events of: (a) July 27, 2009; (b) July 18, 2009; (c) September 27, 2009; and (d) June 28, 2010. Hatched zones represent the volume fractions identified as 'initial' and 'final' phases.

Finally, the event of June 28 does not reproduce the typical three phases, which can be explained by the sand sent to sewers during roadwork. Impacts of roadwork were also visible at the inlet (see 'Filling period' section). Table 3 shows that seven events were correctly sampled during the two summers (initial, middle and final phases).

Table 3 focusses on these three phases showing TSS concentrations and loads within each phase for 15 events. Loads are calculated according to Equation (2). Thus, it takes into account the concentration variability within the phase. Total load percentages were not calculated when one of the phases was missed. Concentrations presented for the 'initial' and 'final' phases are the maximum concentrations within each phase. Average of these concentrations over all the events are  $7,109 \text{ g/m}^3$  for 'initial' and  $580 \text{ g/m}^3$  for 'final' phases (the peak is assumed to end/start when

the concentration decreases less rapidly, mainly around  $100 \text{ g/m}^3$ ). It is the range of values during the 'middle' phase that is reported in Table 3. Indeed, the lower concentration within the 'middle' phase gives an indication of the settling efficiency within the tank. Typically, this minimal value is reached for the last sample taken before the 'final' peak.

TSS loads reveal that the largest fraction of the emptied mass is released during the 'middle' phase with an average of  $529 \text{ kg}$  of TSS (Table 3). However, that mass is transferred to the WWTP by the largest volume of water resulting in the lowest concentration of the three phases (median between  $69$  and  $129 \text{ g/m}^3$ ). Until the end of June 2010 (before the beginning of the roadwork), it is of interest to note that the 'middle' phase concentration is similar for each event, even though the stagnant period (idle time between the

**Table 3** | TSS concentrations, loads and percentages of total mass for the three phases of the emptying

|                | Initial phase             |            |           | Middle phase              |            |           | Final phase               |           |           |
|----------------|---------------------------|------------|-----------|---------------------------|------------|-----------|---------------------------|-----------|-----------|
|                | Conc. (g/m <sup>3</sup> ) | Load (kg)  | Perc. (%) | Conc. (g/m <sup>3</sup> ) | Load (kg)  | Perc. (%) | Conc. (g/m <sup>3</sup> ) | Load (kg) | Perc. (%) |
| 18/7/2009      | 338                       | 86         | –         | 55–100                    | 94         | –         | –                         | –         | –         |
| 27/7/2009      | 1,920                     | 160        | 22        | 55–100                    | 505        | 68        | 629                       | 75        | 10        |
| 18/8/2009      | 768                       | 99         | 20        | 71–122                    | 333        | 65        | 256                       | 75        | 15        |
| 21/8/2009      | –                         | –          | –         | 69–129                    | 166        | –         | 844                       | 80        | –         |
| 27/9/2009      | 5,623                     | 126        | 15        | 27–47                     | 582        | 73        | 567                       | 85        | 12        |
| 3/10/2009      | 1,311                     | 41         | –         | 43–132                    | 328        | –         | –                         | –         | –         |
| 6/6/2010       | 1,329                     | 28         | 12        | 33–87                     | 150        | 66        | 473                       | 50        | 22        |
| 25/6/2010      | 205                       | 60         | –         | 73–114                    | 690        | –         | 73                        | –         | –         |
| 28/6/2010      | 2,045                     | 120        | 10        | 369–1,416                 | 1,005      | 79        | 494                       | 144       | 11        |
| 9/7/2010       | –                         | –          | –         | 156–258                   | 796        | –         | 386                       | 55        | –         |
| 13/7/2010      | 6,124                     | 219        | 56        | 48–85                     | 144        | 36        | 238                       | 30        | 8         |
| 16/7/2010      | 49,936                    | 1,184      | 37        | 97–536                    | 1,835      | 57        | 1,910                     | 188       | 6         |
| 22/7/2010      | 811                       | –          | –         | 97–700                    | –          | –         | 492                       | –         | –         |
| 3/8/2010       | 21,503                    | 526        | –         | 51–186                    | 406        | –         | –                         | –         | –         |
| 13/9/2010      | 500                       | 22         | –         | 154–202                   | 378        | –         | –                         | –         | –         |
| <b>Average</b> | <b>7,109</b>              | <b>223</b> | <b>25</b> | <b>93–280</b>             | <b>529</b> | <b>63</b> | <b>580</b>                | <b>87</b> | <b>12</b> |
| <b>Median</b>  | <b>1,311</b>              | <b>109</b> | <b>20</b> | <b>69–129</b>             | <b>392</b> | <b>66</b> | <b>473</b>                | <b>75</b> | <b>11</b> |

– = non-analysed.

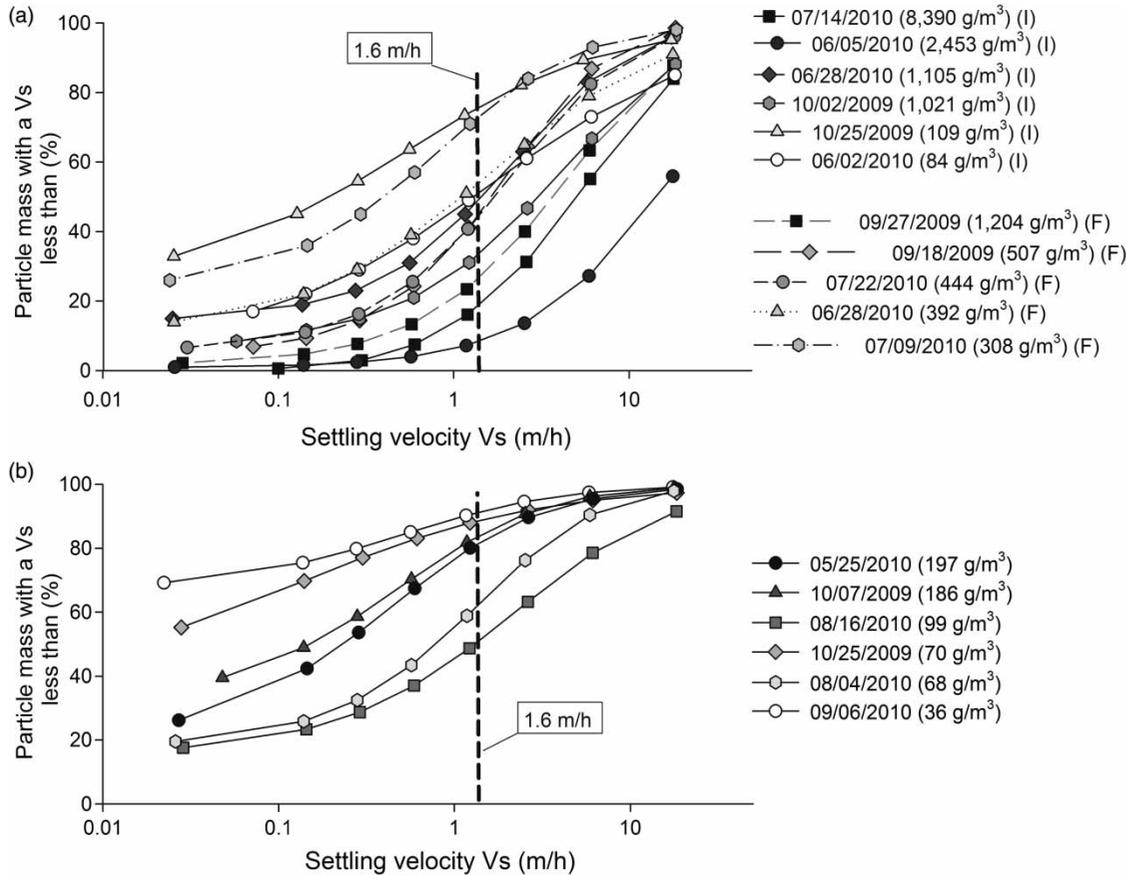
end of filling and the beginning of the emptying that allows for quiescent settling) in the RT varies between 5 and 240 minutes. It might give an indication about the impact of storage time on treatment efficiency. This point is more detailed below under Retention time impact on settling efficiency.

The percentages column of Table 3 represents the percentage of the total emptied mass that is released during the corresponding period. It is important to emphasise that the average of the percentages (last row in bold) is highly impacted by two events, July 16, 2010 and August 3, 2010. The ‘initial’ phase maximum concentrations reach 49,936 and 21,503 g/m<sup>3</sup>, respectively. Those are very high values and correspond to the previously mentioned roadwork on the catchment. The median was also calculated because it is less impacted by extreme values. The maximal concentration median becomes 1,311 g/m<sup>3</sup>, which is more representative of the majority of events. However, one can note the similarity between the average and the median values when considering the percentages of particle mass.

They show that around 23% of the mass is returned to the WWTP within the ‘initial’ peak, 12% within the ‘final’ and 65% within the middle phase.

### Settling velocity and TSS concentration

As for the inlet, ViCAs tests were carried out on samples collected during each phase of emptying. In Figure 4(a), ViCAs performed on samples from the ‘initial’ (‘I’) and the ‘final’ (‘F’) phases are shown on the same graph because concentrations are of the same order of magnitude. The average of these sample TSS concentrations is 1,520 g/m<sup>3</sup>. TSS concentrations for each sample are written in parentheses in the legend (in g/m<sup>3</sup>). One can note that, generally, around 40% of the total particle mass of the sample has a Vs less than 1.6 m/h. For the ‘middle’ phase, that fraction is closer to 80% for an average TSS concentration of 109 g/m<sup>3</sup>. This observation confirms that the ‘middle’ phase corresponds to the release of settled waters. Indeed, most of the particles with high Vs have settled and then, clarified waters remain.



**Figure 4** | VICAS curves from various events collected within: (a) the ‘initial’ (I) and the ‘final’ (F) phases; and (b) the ‘middle’ phase. In parentheses, the TSS concentrations for each sample in  $\text{g/m}^3$ . The grey colour gradient reflects the TSS concentrations (dark = high concentrations).

One can note that the relationship between concentration and PSVD becomes more evident with high concentrations. When comparing the concentration and the PSVD of Figures 2 and 4(b) to those of Figure 4(a), the concentrations are higher when the fraction of particles with high  $V_s$  is larger.

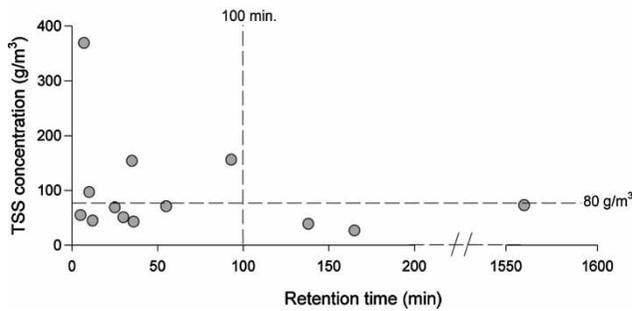
**Retention time impact on settling efficiency**

As previously discussed, water coming from the ‘middle’ emptying phase corresponds to the bulk volume out of which heavier sediments have settled. A slow further decrease of TSS concentrations is observed within that phase. That is to say, a slow settling process is on-going, even during emptying. Thus, the lowest concentration within that phase is the result of the settling which takes place in the tank. Further calculations (Equation (5)) take

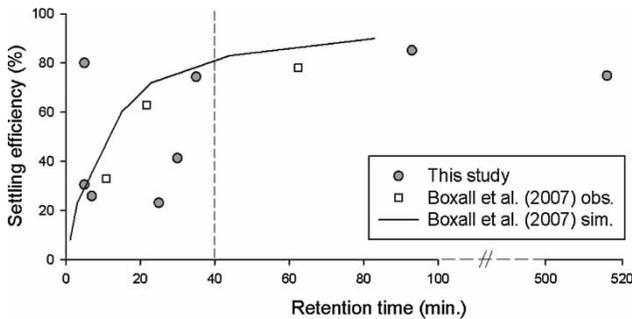
into account this minimum value within the ‘middle’ phase rather than the average of the range because high values can be due to particular short events, such as an activation of the pumps that resuspend particles for a few minutes. Even though it is a simplification, it is considered to be the most adequate way to calculate it.

Figure 5 presents the TSS concentrations of the ‘middle’ phase as a function of the retention time of each event. Most events have retention times below 200 minutes and TSS concentrations below  $160 \text{ g/m}^3$ . One can note that, for retention times higher than 100 minutes, TSS concentrations do not exceed  $80 \text{ g/m}^3$ . However, there are insufficient points above 100 minutes to conclude a clear relationship.

Figure 6 presents the settling efficiency as a function of retention time. The settling efficiency, based on load calculations (Equation (2)), follows Equation (5) where  $L_{\text{TSS middle}}$  (kg) corresponds to the TSS load released



**Figure 5** | Minimum 'middle' phase concentrations as function of retention time for 13 events sampled during the 2009 and 2010 summers: TSS concentration.



**Figure 6** | Settling efficiency versus retention time for 10 events sampled during the 2009 and 2010 summers.

within the 'middle' phase of the emptying.  $L_{TSS \text{ inlet}}$  represents the TSS load entering the tank.

$$\begin{aligned} \text{Settling efficiency (\%)} &= \frac{L_{TSS \text{ settled}}}{L_{TSS \text{ inlet}}} \times 100 \\ &= \frac{L_{TSS \text{ inlet}} - L_{TSS \text{ middle}}}{L_{TSS \text{ inlet}}} \times 100 \quad (5) \end{aligned}$$

For retention times lower than 40 minutes, the settling efficiency varies between 20 and 80% and no correlation exists between settling efficiency and retention time within that period. For a retention time longer than 40 minutes, the small quantity of data does not permit establishing a real correlation. However, observing that the efficiency on the TSS reaches more than 80% for the events of July 9, 2010 and July 13, 2010, provides information on the order of magnitude of the efficiency for other hypothetical events. Furthermore, results presented by Boxall *et al.* (2007), tend to confirm the trend observed in this study. A threshold seems to appear after 40 minutes both on measurement and modelling data.

## CONCLUSION

New data on the water quality of retained overflow water are presented in this paper, leading to a better database on water quality in combined sewers and, more specifically, on RTs. Knowledge of the phenomena occurring in RTs is consolidated.

During the filling of a RT, two different periods are highlighted with respect to TSS and CODt concentrations. Each period could be linked to a specific PSVD. These two periods are differentiated on the basis of the first-flush phenomenon with: (1) the 'wash-off' period which is usually associated with high concentrations. In these waters, between 30 and 40% of the particle mass fraction has a  $V_s$  less than 1.6 m/h; and (2) the 'dilution' period (following the 'wash-off') which is characterised by a low pollutant concentration. Between 40 and 80% of the particle mass fraction has a  $V_s$  less than 1.6 m/h.

During tank emptying, the pollutographs can be split in three different phases. Similar to the inlet, these phases are correlated to specific PSVDs. The three phases are as follows:

1. The 'initial' phase is characterised by a pollutant concentration peak due to the drawing of the accumulated matter from the previous event at the bottom of the pumping well (TSS EMC average = 7,100 g/m<sup>3</sup>). Similar to the inlet behaviour, that peak of concentration is correlated to a higher fraction of particles with high  $V_s$ .
2. The 'middle' phase characteristics are the result of the settling processes occurring in the tank during storage. Thus, concentrations during that phase are lower and particles have a low  $V_s$  (TSS EMC average = 93 g/m<sup>3</sup>). Around 80% of the particle mass fraction has a  $V_s$  less than 1.6 m/h.
3. The 'final' phase corresponds to a peak of pollutant concentration that occurs within the last 10 minutes of pumping. It is due to the pumping well energy in the small volume that draws up the settled particles from the pumping well. PSVDs are similar to those from the 'initial' phase.

Finally, concerning the pollutant settling efficiency, it appears that the retention time has no significant impact on the treatment efficiency for retention times below 40 minutes.

## ACKNOWLEDGEMENTS

The authors want to thank the retEAU team and the financial support of the FRQNT (Fonds de Recherche du Québec sur la Nature et les Technologies). Peter Vanrolleghem holds the Canada Research Chair in Water Quality Modelling and was Otto Mønsted Guest Professor at the Technical University of Denmark in 2012–2013.

## REFERENCES

- Aires, N., Chebbo, G., Tabuchi, J. P. & Battaglia, P. 2003 Dépollution des effluents urbains de temps de pluie en bassins de stockage décantation. *TSM* **12**, 70–86 (in French).
- APHA, AWWA, WEF 2012 *Standard Methods for Examination of Water and Wastewater*, 22nd edn. American Public Health Association, Washington, DC, USA, pp. 1496.
- Ashley, R. M., Dudley, J., Vollertsen, J., Saul, A. J., Jack, A. & Blanksby, J. R. 2002 The effect of extended in-sewer storage on wastewater treatment plant performance. *Water Sci. Technol.* **45** (3), 239–246.
- Bertrand-Krajewski, J. L., Chebbo, G. & Saget, A. 1998 [Distribution of pollution mass vs. volume in stormwater discharges and the first flush phenomenon](#). *Water Res.* **32** (8), 2341–2356.
- Boxall, J., Saul, A. & Shepherd, W. 2007 *Performance of Storm Tanks and Potential for Improvements in Overall Storm Management – Phase 2. Wastewater Treatment and Sewerage: Collection Systems WW/22*. Gordon Rogers, Yorkshire Water Services Ltd, UK Water Industry Research, London, UK.
- Brechenmacher, M., Wirth, H. & Gaeffgen, K. 1992 Investigations on large stormwater retention tanks in Munich. *Water Sci. Technol.* **26** (9–11), 2489–2492.
- Calomino, F., Piro, P. & Palma, G. 2004 Combined sewer overflows into the Crati river (Cosenza, Italy) and retention storage sizing. In: NATO Advanced Research Workshop on Enhancing Urban Environment by Environmental Upgrading and Restoration, November 6–9, 2003, Rome, Italy, pp. 139–149.
- Chebbo, G. & Gromaire, M. C. 2009 [VICAS – an operating protocol to measure the distributions of suspended solid settling velocities within urban drainage samples](#). *J. Environ. Eng.* **135**, 768–775.
- Chebbo, G., Gromaire, M. C., Ahyerre, M. & Garnaud, S. 2001 Production and transport of urban wet weather pollution in combined sewer systems: the ‘Marais’ experimental urban catchment in Paris. *Urban Water* **3**, 3–15.
- Deletic, A. 1998 [The first flush load of urban surface runoff](#). *Water Res.* **32** (8), 2462–2470.
- Diaz-Fierros, T. F., Puerta, J., Suarez, J. & Diaz-Fierros, V. F. 2002 Contaminant loads of CSOs at the wastewater treatment plant of a city in NW Spain. *Urban Water* **4**, 291–299.
- Ellis, B. 1991 Urban runoff quality in the UK: problems, prospects and procedure. *Appl. Geog.* **11**, 187–200.
- Gromaire-Mertz, M.-C. 1998 La pollution des eaux pluviales urbaines en réseau d’assainissement unitaire caractéristiques et origines. PhD Thesis, École Nationale des Ponts et Chaussées, Paris, France, pp. 507+annexes; in French.
- Gromaire-Mertz, M. C., Garnaud, S., Gonzalez, A. & Chebbo, G. 1999 [Characterisation of urban runoff pollution in Paris](#). *Water Sci. Technol.* **39** (2), 1–8.
- Howard, K., Saul, A. J., Thornton, R. C. & Pearson, L. G. 1986 *The Effects of Combined Sewer Overflows upon Receiving Waters*. Urban Stormwater Quality and Effects upon Receiving Waters. Commissie voor Hydrologisch Onderzoek TNO, The Netherlands.
- Kafi, M., Gasperi, J., Moilleron, R., Gromaire, M. C. & Chebbo, G. 2008 [Spatial variability of the characteristics of combined wet weather pollutant loads in Paris](#). *Water Res.* **42**, 539–549.
- Lessard, P. 1989 Operational Water Quality Management: Control of Stormwater Discharges. PhD Thesis, Department of Civil Engineering, Imperial College of Science, Technology and Medicine, London, UK, pp. 389.
- Lessard, P. & Lavallée, P. 1985 [Caractéristion des eaux usées de débordements de réseau unitaire](#). *Can. J. Civ. Eng.* **12**, 527–537. in French.
- Lindholm, O. 1985 May retention basins have an overall negative effects? *Vatten* **41**, 214–217.
- Maruejols, T., Lessard, P., Wipliez, B., Pelletier, G. & Vanrolleghem, P. A. 2011 [Characterisation of the potential impact of retention tank emptying on wastewater primary treatment: a new element for CSO management](#). *Water Sci. Technol.* **64** (9), 1898–1905.
- Maruéjols, T., Vanrolleghem, P. A., Pelletier, G. & Lessard, P. 2012 [A phenomenological retention tank model using settling velocity distributions](#). *Water Res.* **46**, 6857–6867.
- Metcalf & Eddy 2003 *Wastewater Engineering Treatment and Reuse*, 4th edn. McGraw-Hill, NY, USA.
- Michelbach, S. & Weiß, G. J. 1996 [Settleable sewer solids at stormwater tanks with clarifier for combined sewage](#). *Water Sci. Technol.* **33** (9), 261–267.
- Rechenburg, A., Koch, C., Classen, T. & Kisteman, T. 2006 [Impact of sewage treatment plants and combined sewer overflow basins on the microbiological quality of surface water](#). *Water Sci. Technol.* **54** (3), 95–99.
- Shu, W.-P. 2004 The Use of a Water Quality Model to Evaluate the Impacts of Combined Sewer Overflows on the Lower Hudson River. PhD Thesis, Department of Civil and Environmental Engineering, Faculty of New Jersey Institute of Technology, New Jersey, USA, 222 pp.
- Suarez, J. & Puertas, J. 2005 [Determination of COD, BOD, and suspended solids loads during combined sewer overflow \(CSO\) events in some combined catchments in Spain](#). *Ecol. Eng.* **24** (3), 201–219.
- Sztruhár, D., Sokac, M., Holiencin, A. & Markovic, A. 2002 [Comprehensive assessment of combined sewer overflows in Slovakia](#). *Urban Water* **4**, 237–243.