Characterization of the potential impact of retention tank emptying on wastewater primary treatment: a new element for CSO management

T. Maruejouls, P. Lessard, B. Wipliez, G. Pelletier and P. A. Vanrolleghem

ABSTRACT

Theoretical studies have shown that discharges from retention tanks could have a negative impact on the WWTP's (Wastewater Treatment Plant) effluent. Characterization of such discharges is necessary to better understand these impacts. This study aims at: (1) characterizing water quality during emptying of a tank; and (2) characterizing the temporal variation of settling velocities of the waters released to the WWTP. Two full-scale sampling campaigns (18 rain events) have been realized in Quebec City and laboratory analyses have shown a wide variability of total suspended solids (TSS) and Chemical Oxygen Demand (COD) concentrations in the water released from the tank. Suspended solids seem to settle quickly because they are only found in large amounts during the first 15 min of pumping to the WWTP. These solids are hypothesized to come from the pumping in which solids remained after a previous event. When these solids are evacuated, low TSS containing waters are pumped from the retention tank. A second concentration peak occurs at the end of the emptying period when the tank is cleaned with wash water. Finally, settling velocity studies allowed characterizing combined sewer wastewaters by separating three main fractions of pollutants which correspond to the beginning, middle and end of emptying. In most cases, it is noticed that particle settling velocities increase as the pollutant load increases.

Key words | combined sewer overflow, integrated urban wastewater system, retention tank, settleability characteristics, stormwater, wastewater fractionation

T. Maruejouls
P. Lessard (corresponding author)
B. Wipliez
G. Pelletier
P. A. Vanrolleghem
Département de génie civil et de génie des eaux, Université Laval,
1065 av. de la Médecine,
Québec, Qc,
Canada G1V 0A6
E-mail: *Paul.Lessard@gci.ulaval.ca*

INTRODUCTION

In the context of operational water management (Beck 1981) retention tanks, commonly used to minimize the impact of combined sewer overflows (CSO) on receiving water bodies, can no longer be considered only as a treatment alternative, but should be viewed as a proactive tool for water management of urban systems. To maximize the environmental benefits of retention tank implementation, one must make sure that the tanks are well managed individually, but very importantly also as a system integrated within the collection system and the WWTP. This is a challenge, because the management of retention tanks is dichotomous, as already shown 25 years ago by Lindholm (1985) and explained below.

During and after rainfall events, urban catchments can generate excessive runoff, leading to hydraulic overloads to the WWTP and additional pollution to be dealt with. Lindholm (1985) wondered whether retention was really an overall positive solution for an urban system: the emptying of the retention tanks, depending on the hydraulic and environmental conditions at that moment, could degrade the WWTP's effluent to such an extent that an overall negative impact on the system could be created. Indeed, the increased hydraulic load at the WWTP due to the emptying of retained combined sewage impacts the treatment efficiency over a long period of time. Lindholm's study, albeit theoretical, asked the question abruptly, and it has yet to be answered clearly. Calabro & Viviani (2006) identified that one of the challenges for the future will be to take into account the effects of retention tanks on the WWTP, in order to optimize the size of the tanks and to minimize overall overflows to the receiving water bodies, i.e. to minimize the total loads from both the sewer overflows and the treatment plant's effluent.

doi: 10.2166/wst.2011.763

Several theoretical studies have been conducted to try and provide an answer (e.g. Lessard & Beck 1990; Bauwens *et al.* 1996). In all cases, the authors show the potential impacts of retention tank emptying on the WWTP (especially in terms of TSS removal efficiency) and the importance of analysing the urban system as a whole to properly quantify the benefits of the implementation of retention tanks. The main negative impacts of the increase in hydraulic load on several WWTP structures as aeration tanks or primary and secondary settlers are, respectively, the sludge wash out and the increase in overflow rate. While there are studies on retention tanks (e.g. Aires *et al.* 2003), no field study has been identified on the specific subject of emptying. This research project was thus developed to analyse the interactions between the retention tank and WWTP in a real case study. In an initial step, emptying waters from a retention tank were characterized and the effect of distinctive operating conditions of the emptying on the emptying water's quality was identified.

The purpose of this paper is thus to characterize the emptying waters and compare them with the WWTP's typical dry weather influent, especially in terms of settleability, a key parameter for the treatment of such waters.

METHODOLOGY

Analyses were mainly done to characterize suspended solids (SS), since much of the pollution loads are linked to SS (Michelbach 1995; Ashley *et al.* 2004; Rossi 2004). This characterization has been done in two main steps:

(1) Monitoring the pollutant concentrations during the emptying of the tank in terms of suspended solids (SS) and organic matter (COD);
(2) Characterizing the evolution of the settling velocities of particles during emptying.

Watershed characteristics

The off-line retention tank in this study is located downstream of a Quebec City urban catchment. The total area is 1.46 km^2 with an average imperviousness of 51%. The land use includes 28% institutions, 41% residential, 12% commercial, 12% industrial and 7% green areas. The catchment is separated in two parts: the upstream is composed essentially of residencies and institutions and is located about 70 m higher than the second, which mainly contains commercial areas and industries. The concentration time is about 26 min and the total population is estimated to be around 5,200 habitants. The retention tank has a capacity of 7,580 m^3 and was designed for four overflows per summer.

Tank operation

The retention tank is rectangular in shape and comprises two parts. The first one is the control chamber located online the interceptor. Its role is to derive flows to the tank when certain conditions are met (e.g. high water levels in the interceptor, high flow rates at the inlet of the WWTP). The other part is the tank itself, which is located 200 m downstream the control chamber. This retention tank is the most distant from Quebec City's East WWTP (5 km) amongst the nine other tanks located along the same interceptor. The travel time between the site and the WWTP is approximately 1 h 30 min (Figure 1). Wastewater can follow four paths (Figure 2):

(1) During dry weather, the flow passes the control chamber and goes into the interceptor to the WWTP;
(2) During wet weather, the rising level in the control chamber leads to an overflow over a weir to a 200 m long pipe which ends in the tank;
(3) When the tank is full, the inlet is closed. Then, the water level rises in the control chamber until it reaches the overflow pipe. All the exceeding flow is then routed to the St Charles river;
(4) Once the spilling has stopped and the conditions in the interceptor allow it, the pumps located downstream of the tank are activated and tank emptying begins. Water is returned to the control chamber in order to be sent to the WWTP via the interceptor.
(5) At the end of emptying, the cleaning system is switched on. The principle is to release water, from storage cells located upstream of the tank providing a high enough flow velocity to remove settled particles. The cells are first filled up with the stormwater entering the tank at the beginning of the event.

The whole system is equipped with several sensors for its real-time operation. These sensors include nine level meters (lit 00X, Figure 2) allowing estimations of flows and volumes.

Sampling campaigns

The data were collected during two sampling campaigns in the summers of 2009 and 2010. Sampling consisted in collecting water at the outlet of the tank. Several samples were

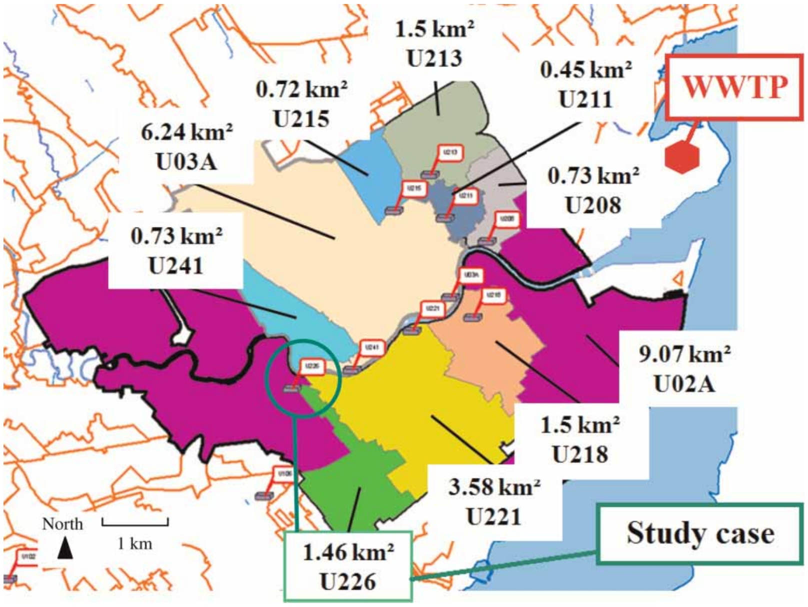

Figure 1 | Urban catchments and retention tanks linked to the Quebec City's East WWTP with their respective surfaces. The study case is the retention tank U226.

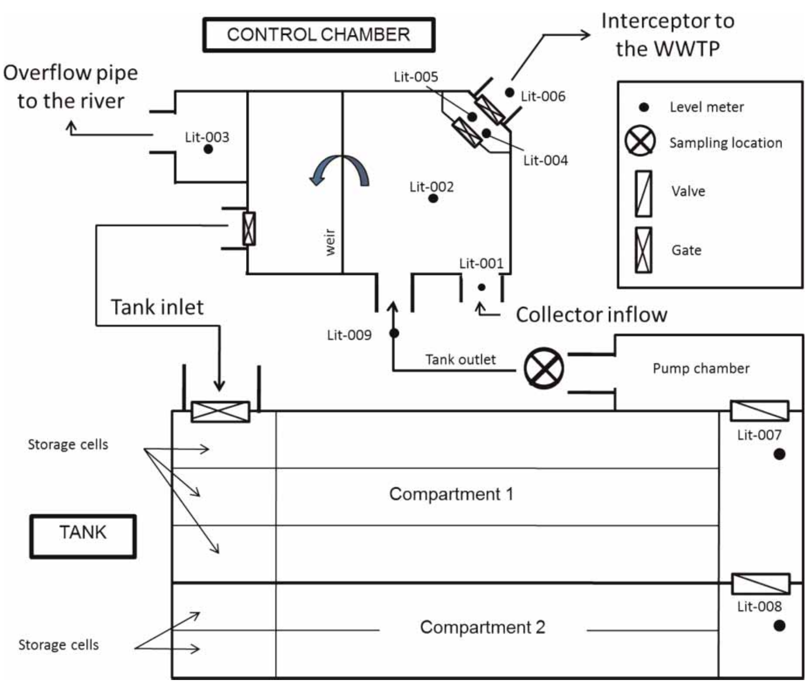

Figure 2 | Schematic of the retention tank (lit-00X means level meter N°X).

taken with a variable time interval (2 min to 2 h) during each event. These time intervals were set in order to observe all pollutant concentration dynamics during emptying. These data were compared with wastewater sampled at the East WWTP of Quebec City after the grit chambers and at the outlet of the primary settler. Some 20 grab samples were collected during night and day, at different times throughout the year. Those samples were then analysed at the Université Laval's environmental laboratory, mainly for SS, COD and settling velocity distribution (Vs); see below.

At the retention tank, grab samples were collected with an automatic sampler (*SIGMA 900max)* connected to a float switch (FLYGT ENM-10). The sampler is located at the outlet of the tank, just after the pumps (Figure 2). Those samples were then mixed to have composite samples for Vs characterization.

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 characterization. Those tests showed that it is acceptable to carry out the measurements within the following 24 h.

The TSS analyses were performed according to Standard Methods (APHA *et al.* 2005). Total COD was analysed with the Hach closed-reflux method (method Hach 8000) after grinding and homogenization of the samples. Measurements of the Vs distributions were carried out using the ViCAs protocol (Chebbo & Gromaire 2009) on both composite and grab samples. It gives the mass percentage of particles that have a Vs lower than the velocity noted on the *X*-axis.

Flux calculation

Flux calculations were carried out for four emptying events, i.e. when the pollutograph was complete and showing all the variability in concentrations. The fluxes were calculated using the linear interpolation method of concentration points (Kronvang & Bruhn 1996). Masses were calculated by integrating the fluxes. Equation (1):

$$\hat{L} = \sum_{i=0}^{n+1} \sum_{t_i < t \le t_{i+1}}^{i} q_{t\,*} \frac{c_{tj}(t_{j+1} - t) + c_{tj+1}(t - t_j)}{t_{j+1} - t_j} \tag{1}$$

The flux (g/h) depends on the flow (q_t in m^3/h) and the concentration (c_t in g/m^3) for time step t (in h). That equation must be chosen when the time interval of flows is shorter than the concentrations' time interval. The level meter system provides volumes in the tank with a quite good accuracy and high frequency (1 min interval). Those data were used to determine the flow at the outlet. Indeed, the sensors are located close to the pumps (one 7 m away, the other one at around 15 m) which permits to adequately represent the variation of the volume.

RESULTS AND DISCUSSION

Rain event characteristics

More than 18 rainfall events were sampled during the summers of 2009 and 2010. The characteristics of those events are summarized in Table 1. Many different types of storms were sampled. For example, the maximum intensity for 5 min covers a range from 1.2 to 45.6 mm/h, total precipitations are between 0.8 and 45.7 mm and volumes retained in the tank between 460 and 7,580 m^3 (full tank). One can note that the quiescent times (i.e. when there is no flow coming in or out, and thus water is stored under stagnant conditions before pumps start emptying the tank) in 2009 are shorter than 1 h except for the event of September 27th, which is due to the long duration of the rain (25 h 30 min). The quiescent times are longer in 2010, which is probably due to the mechanical problems the pumps suffered from because of roadworks on the watershed, which led to a huge quantity of sand drained into the combined sewers.

Water quality: dry weather

Characterization of the Vs distribution during dry weather conditions was carried out on samples from the East WWTP of Quebec City. The results are shown in Figure 3. A coloured zone represents the range of settling velocities observed in the samples from a certain site, i.e. the upper and lower lines are the maximum and minimum of values collected. The dark range consists of three samples (three Vs distribution curves) collected at different times at the outlet of primary treatment. The grab sample TSS concentrations are between 36 and 98 mg/l. The pale range is the average of 13 samples collected before the grit chamber and the primary settler. The TSS grab sample concentrations vary from 77 to 623 mg/l.

A ViCAs curve must be interpreted as follows: the lower the curve the larger the fraction of rapidly settling particles. Considering a sedimentation velocity of 1.6 m/h (40 m^3/m^2*d) to be the typical design overflow rate for primary sedimentation units (Metcalf & Eddy 2003), Figure 3 shows that between 83% and 91% of the particle masses at the outlet of the primary settler have a Vs lower than their design value (1.6 m/h). Furthermore, one can note that between 44 and 78% of the influent particle masses have settling velocities lower than 1.6 m/h, resulting in 56 to 22% of particle masses that can be intercepted by a primary settler.

Table 1 | Rainfall characteristics

Date (dd/mm)	Duration (h)	Cumulated height (mm)	Max. intensity for 5 min (mm/h)	Previous dry weather period (h)	Quiescent time in the tank (min)	Volume in the tank (m^3)
18-07-09	2h25	13.1	44.4	18.75	5	3.100
27-07-09	0h55	6	25.2	6	5	4.064
17-08-09	0h10	2.2	25	189	10	480
18-08-09	01h00	7.5	21.6	19	55	2.700
21-08-09	0h50	3	3.6	18	25	1.950
23-09-09	1h40	1.8	9.6	25	15	460
27-09-09	25h30	45.7	16.8	90	240 and 50[a]	7.400
02-10-09	10h40	0.8	1.2	8	30	4.600
07-10-09	18h00	23.7	10.8	34	30	6.780
01-06-10	13h25	29.6	18	24	1.360 and 15[a]	7.406
06-06-10	27h20	11.3	6	60	20 and 17[a]	2.548
24-06-10	08h40	22.7	42	103	1.560	7.398
28-06-10	00h30	4.7	45.6	61	7	969
09-07-10	09h45	14.2	36	213	93	4.189
13-07-10	03h40	6.6	7.2	89	15 and 516[a]	1.869
16-07-10	01h15	6.1	15.6	53	10	2.785
21-07-10	01h30	2.9	4.8	133	2	653
03-08-10	04h50	29	19.2	230	30	4.036

[a]Both values are respectively for first and second emptying phases.

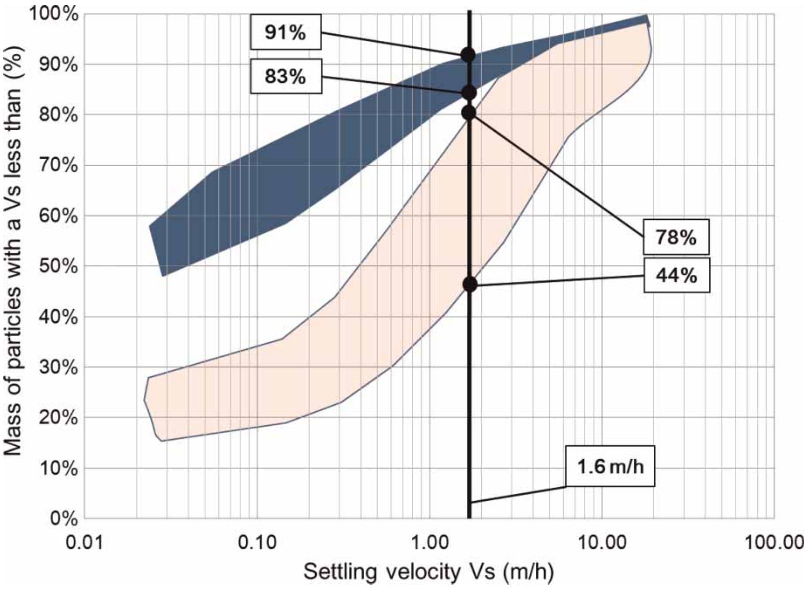

Figure 3 | Vs distribution curves for dry weather wastewater. 'Dark' is the Vs distribution range of wastewaters from the effluent of primary settling. 'Pale' is the Vs distribution range of wastewaters from the influent of primary settling.

Water quality: tank emptying

Sampling during tank emptying was carried out for more than 18 events during the summers of 2009 and 2010. A huge variability of pollutant concentrations during emptying is observed. Measured TSS concentrations vary from 27 to more than 20,000 mg/l. In terms of COD, the observations are similar with concentrations varying between 32 and 4,000 mgO_2/l. For most of the events, concentrations remain within the ranges reported in literature for combined sewers: around 176 to 2,500 mg/l for TSS and 42 to 900 mg O_2/l for COD (Metcalf & Eddy 2003; Bertrand-Krajewski 2006). However, for a few events the concentrations are largely exceeding these values. These extreme values can be linked to the roadworks on the watershed that brought a large quantity of sand in the pipes. Generally, the maximum value is reached at the beginning of the emptying as the pumps start to draw water from the well where sediments have accumulated. Some of the variability can also be linked to characteristics of the rainfall event (e.g. intensity, duration, antecedent dry weather period …) and the retention time in the tank. Indeed, the antecedent dry weather period is an important factor in the pollutants' accumulation on the watershed before their wash-off, which is mainly controlled by the intensity and the duration of the rain (Ashley *et al.* 2004; Brière 2006). Finally, the longer the retention time in the tank, the more particles settle.

Two typical pollutographs for emptying waters are shown in Figure 4. In fact, TSS present in the first peak arises from the cleaning of the previous event, i.e. solids trapped in the pumping well. In fact, the cleaning system consists in suddenly releasing 25 m^3 of wastewaters at the end of emptying (when there is almost no more water remaining in the tank). The energy coming with the washing water is enough to push all settled particles to the pumping well. Since the pumps are submerged, waters remaining in the pumping well after their shutdown contain a high quantity of settled particles. That matter is resuspended at the beginning of the next pumping activation. Consequently, the value of the concentration at this first peak cannot be linked to the current event characteristics, but should be linked to the characteristics of the previous one.

For the July 27th 2009 event (Figure 4(a)), the last peak is not well represented because of the lack of data points collected. If samples had been collected at higher frequency, it would be expected to have had a shape similar to the one shown in Figure 4(b). Indeed, the increase in TSS concentration is only due to the cleaning system activated during the last 10 min of the emptying period (as Figure 4(b) shows).

For most of the rain events three distinct phases can be observed during emptying: the beginning, the middle and the end. During the middle phase, the TSS concentrations are quite constant around 80 mg/l, while during the two other phases, the TSS concentrations are high and variable.

For both events mass fluxes were calculated with Equation (1), showing that about 10% of the TSS load is returned within the first 15 min, 70% in the middle phase and 20% in the last 15 min of emptying.

For each of the three emptying phases, Vs analyses were carried out (Figure 5). The curves represent the averages of (1) Vs distributions of particles contained in wastewaters from the middle phase (upper curve average of three samples) and (2) Vs distributions of particles contained in wastewaters from the beginning and the end of emptying (lower curve average of six samples). The second curve combines Vs distributions from the beginning and the end phases as they are similar. Figure 5 also shows that the particles from the middle portion of emptying have a Vs distribution similar to that of the effluent of primary settling (dark range). Moreover, particles contained in the waters from the beginning and the end of emptying tend to settle faster than those collected before the grit chamber (pale

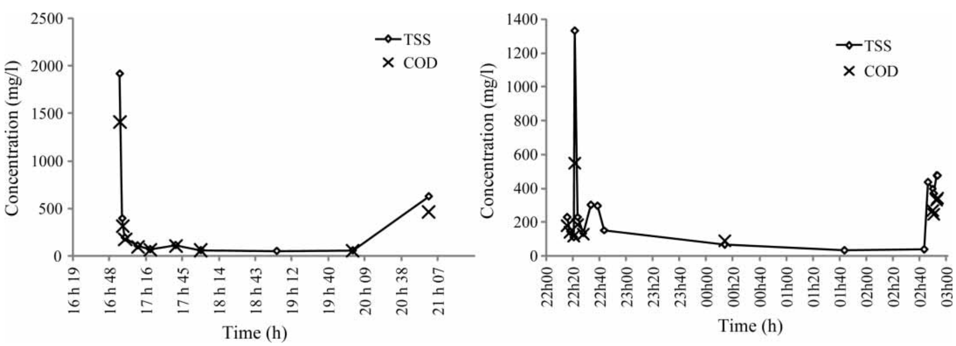

Figure 4 | TSS and COD concentrations at the outlet of the retention tank for different events: (a) July 27th 2009; (b) June 6th 2010.

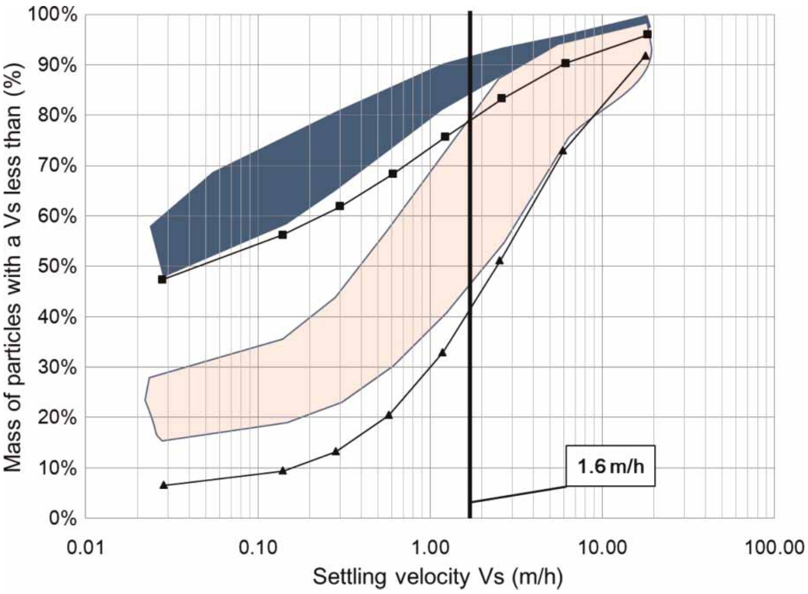

Figure 5 | Vs average curves for emptying waters versus Vs curves for dry weather. Square symbols represent the average of the Vs distributions of particles from water released during the middle of emptying. Triangle symbols represent the average of the Vs distributions of particles from water released at the end and at the beginning of emptying. Dark and pale ranges are the same as in Figure 3.

range), which means that they will be removed by a primary settler.

Table 2 presents the characteristics of the ViCAs results used to plot Figure 5. One can observe that the concentration average at the outlet of the tank (beginning and end) is the highest (1,765 mg/l) and corresponds to wastewaters containing a fraction of particle mass which settles the fastest. Indeed, 80% of the particle mass contained in those waters has a Vs lower than 7.46 m/h and 20% lower than 0.23 m/h. Furthermore, the average TSS concentration at the outlet of the tank (middle) is 68 mg/l with 80% of the particle mass having a Vs lower than 2.5 m/h and 20% lower than 0.015 m/h. Those data reveal that, as the concentration increases, so does the particle settling velocity. The difference observed between the Vs corresponding to the 80 percentile fraction at the outlet of the tank (middle) and the primary settler effluent can be explained by the important range of values (36 to 99 mg/l) which results in a high Vs.

Table 2 | TSS concentrations of samples and Vs (m/h) values for the 20 and 80 percentile in particle fractionation

Sample location	TSS concentration (mg/l) Average *Min–Max*	Vs (m/h) Fraction 20%	Vs (m/h) Fraction 80%
Primary settler influent	**392** *74–623*	0.037	4.3
Primary settler effluent	**76** *74–81*	0[a]	0.56
Outlet of the tank (middle)	**68** *36–99*	0.015	2.5
Outlet of the tank (beginning and end)	**1,765** *392–8,390*	0.23	7.46

[a]Corresponds to non settleable matter (Vs < 0.01 m/h)

CONCLUSION

The settleability of particles contained in waters released to the WWTP was analysed and compared with the influent and effluent of a WWTP's primary sedimentation unit. From this study it can be observed that:

1. For waters at the beginning and end of the emptying period, the mass of solids with a Vs below 1.6 m/h (40 m^3/m^2*d) is low, around 40%, which underlines the fact that most particles released to the WWTP will be removed by primary sedimentation.
2. However, only about 20% of the TSS mass from the middle phase period has a Vs higher than 1.6 m/h. Therefore, 80% of these solids cannot be removed by the primary sedimentation unit. Their settleability curve is actually similar to that of a primary effluent.
3. Overall, within the wastewaters returned to the WWTP, about 30% of the TSS mass will settle in the primary clarifier but the 70% left will have a particle Vs distribution similar to that of a primary settler effluent.

4. ViCAs analyses show that there is a link between the TSS concentrations and the Vs distribution obtained from combined sewer samples. As the concentration increases, so does the settling velocity.

This study provides interesting information regarding the management of emptying waters and their potential impacts. It stresses the fact that a retention tank should be emptied in the context of operational management. For example, emptying must be done after the rain event, when the receiving water flow rate is at its highest (allowing more dilution of emitted pollution), the river watershed reacting more slowly than the urban catchment. Considering that the quality of emptying waters is mostly similar to that of a primary effluent, it might also be considered, depending on environmental constraints, to return these waters directly to the watercourse rather than to the WWTP, as the latter might be hydraulically overloaded, and thus, less efficient. However, it would be equally logical to return waters at the beginning and end of the emptying period to the WWTP, since they are highly loaded with TSS that is removable in primary treatment.

ACKNOWLEDGEMENT

The authors want to acknowledge the ret*EAU* project team, Jeanne Bavard, Elisabeth Vaudevire, Myriam Miville-Godbout, Philippe Carrier-Leclerc, Benjamin Bousquet and Guillaume Samie, for their precious help, and the City of Quebec for its technical support. Funding for this work comes from the Fonds québécois de la recherche sur la nature et les technologies (FQRNT). Peter Vanrolleghem holds the Canada Research Chair on Water Quality Modelling.

REFERENCES

Aires, N., Chebdo, 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).

Ashley, R. M., Bertrand-Krajewski, J.-L., Hvitved-Jacobsen, T. & Verbanck, M. 2004 *Solids in Sewers: Characteristics, Effects and Control of Sewer Solids and Associated Pollutants*. Scientific and Technical Report No. 14. IWA Publishing, London, UK.

APHA, AWWA, WEC 2005 *Standard Methods for Examination of Water and Wastewater*. 21st edition. Centennial Edition. American Public Health Association, Washington, DC.

Bauwens, W., Vanrolleghem, P. A. & Smeets, M. 1996 An evaluation of the efficiency of the combined sewer – wastewater treatment system under transient conditions. *Water Sci. Tech.* **33** (2), 199–208.

Beck, M. B. 1981 *Operational Water Quality Management: Beyond Planning and Design*. Executive report 7, IIASA, Laxenburg, A-2361, Austria.

Bertrand-Krajewski, J.-L. 2006 *Les polluants de rejets urbains de temps de pluie: natures, concentrations, flux, caractéristiques physico-chimiques solides en suspension, et répartition temporelle durant les évènements pluvieux*. Cours d'hydrologie urbaine. INSA, Lyon, France (in French).

Brière, F. G. (ed.) 2006 *Distribution et collecte des eaux*. Presses Internationale: Polytechnique, Montreal, QC, Canada (in French).

Calabro, P. S. & Viviani, G. 2006 Simulation of the operation of detention tanks. *Water Res.* **40**, 83–90.

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.

Kronvang, B. & Bruhn, A. J. 1996 Choice of sampling strategy and estimation method for calculating nitrogen and phosphorus transport in small lowland streams. *Hydrol. Proc.* **10**, 1483–1501.

Lessard, P. & Beck, M. B. 1990 Operational water quality management: control of storm sewage at a wastewater treatment plant. *Res. J. Wat. Pollut. Control Fed.* **62**, 810–819.

Lindholm, O. 1985 May retention basins have an overall negative effect? *Vatten* **41**, 214–217.

Metcalf & Eddy 2003 *Wastewater Engineering Treatment and Reuse*. 4th edition. McGraw-Hill, NY, USA.

Michelbach, S. 1995 Origin, resuspension and settling characteristics of solids transported in combined sewage. *Water Sci. Tech.* **31** (7), 69–76.

Rossi, L. 2004 Modélisation des matières en suspension (MeS) dans les rejets urbains en temps de pluie. *GWA, Gas, Wasser, Abwasser* **10**, 753–761 (in French).

First received 25 February 2011; accepted in revised form 4 July 2011