Retention tank modeling using settling velocity distribution

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ABSTRACT

Many authors have observed the influence of the settling velocity distribution on the sedimentation process in retention tanks. However, the pollutants' behaviour in such tanks is not well characterized, especially with respect to their settling velocity distribution. The present paper has two objectives: 1) to characterize the change of the settling velocity distribution between the inlet and outlet of an off-line retention tank; 2) to improve a dynamic retention tank model (Lessard and Beck, 1991) by implementing a resuspension model due to pump activation during emptying and integrating the particle settling velocity distribution. In the paper, results from sampling campaigns of an off-line retention tank are presented revealing typical "U-shape" TSS concentration dynamics. It is demonstrated that the changes in concentration are associated with changes in settling velocity distribution. Furthermore, a new way to model the sedimentation process during storm events using the settling velocity distribution of particles is proposed. Its potential is demonstrated by comparing model results with full-scale field data.

KEYWORDS

Combined sewer overflow, integrated wastewater modeling; retention tank modeling; settling velocity distribution; wastewater quality; sewer systems.

INTRODUCTION

Retention tanks (RTs) are used in many North American and European cities to reduce the impact of combined sewer overflows (CSO) on receiving water bodies. The goals pursued with RTs can vary from one design to another: intercepting the first flush of pollutants or the first hydraulic peak; carrying out primary treatment of the wastewater by solids separation; or retaining the maximum quantity of combined sewage before sending it back to the wastewater treatment plant (WWTP). Already, in 1985, Lindholm was wondering whether the overall impact of those tanks on the receiving waters was really positive. Actually, emptying the RTs could have a negative impact on the WWTP's treatment efficiency, potentially leading to a higher pollutant load to the receiving waters than from direct overflows. Since then, several theoretical studies have been conducted (e.g. Lessard and Beck, 1990; Bauwens *et al.*, 1996; Lau *et al.*, 2002; Vanrolleghem *et al.*, 2005; Ahnert *et al.*, 2009; Maruejouls *et al.*, 2010). In all cases, the authors investigated the potential impacts of emptying RTs on the WWTP and highlighted the importance of analyzing the urban system as a whole to properly quantify the benefits of implementing RTs. Calabrò and Viviani (2006) suggested that an important issue that remained to be dealt with is the effect of the RTs' emptying water composition on the WWTP. In fact, the goal is to optimize the RT operation to reduce the overall pollution released into the receiving waters.

As integrated modeling is increasingly used in wastewater management, models to simulate the pollutants' behavior in RTs become a necessity to predict the WWTP's influent quality. Indeed, settling is a major process in both RTs and WWTPs since particles carry a broad range of pollutants (Ashley *et al.*, 2004). Two types of models have been developed to represent sedimentation processes in RTs. The first type uses Computational Fluid Dynamics (CFD) to describe the transport of water and particles (Stovin and Saul, 2000; Vazquez *et al.*, 2008). CFD models are useful to optimize the shape of RTs but the time required to solve the equations does not allow their use in integrated urban wastewater management. The second type of models is phenomenological in nature: they represent the dynamics of water and particles in one dimension (Lessard and Beck, 1991; Frehmann *et al.*, 2005). Since they can be used to optimize the design and operation of RTs in an integrated management context, we selected this type of models for our study. It is interesting to note that none of those phenomenological models has actually been validated with full-scale data (Kutzner *et al.*, 2007). They strongly depend on one key characteristic of the particles: the average settling velocity (Vs). However, the average settling velocity is hard to determine due to the large range of Vs found in combined sewage and an average value does not represent well the physical processes. As many authors have mentioned, the distribution of Vs is a factor that could have a large impact on the overall sedimentation process (Huebner and Geiger, 1996; Boxall *et al.*, 2007; Saul *et al.*, 2007), but it is rarely characterized.

The objective of this paper is thus to:

- characterize the change of the settling velocity distribution of the particles in the inlet and the outlet of an off-line RT; and
- improve the Lessard and Beck (1991) RT model by implementing resuspension due to pump activation during emptying and by describing the settling process in a more detailed way.

CHARACTERISATION CAMPAIGN

Materials and methods

Intensive sampling campaigns were conducted on a selected urban catchment in Quebec City during the summers of 2009 and 2010. The 1,54 km^2 catchment is mainly residential with an average imperviousness of around 50%, a concentration time of 26 minutes and an estimated population of 5200 (for more details, see Maruejouls *et al.*, 2010).

The off-line RT is designed to allow an average of four overflows during the summer period (May 15th to September 15th) with a volume of 7580 m^3 and is emptied by pumping after the transport capacity in the main interceptors to the WWTP is regained. Four operation phases are observed in a RT: filling, storage, overflow and emptying. This study mainly focuses on the water's quality during emptying.

The characterisation of the settling of particles was carried out with the ViCAs protocol (Chebbo and Gromaire, 2009), both on composite and grab samples collected at the inlet (downstream of the control chamber's weir) and the outlet (downstream of the pumping chamber, in the pipe leading back to the control chamber) of the RT. The ViCAs protocol is well adapted to the sample volume requirements for analyses (Berrouard, 2010).

Results and discussion

More than 20 events were sampled during the 2009-2010 campaigns. Analysis of the pollutant dynamics reveals a reproducible TSS load pattern for different events. The RT waters sent to the WWTP can be split into **three distinct phases: initial, middle and final phases**, resulting in a **U-shape** TSS concentration profile (Figure 1). Each phase is characterized by specific concentration ranges including the two peaks (initial and final) and a constant TSS concentration at the middle. The mean outflow is around 800 m^3/h for the RT under study. A larger pumping rate is often observed at the end of emptying, although not for this event.

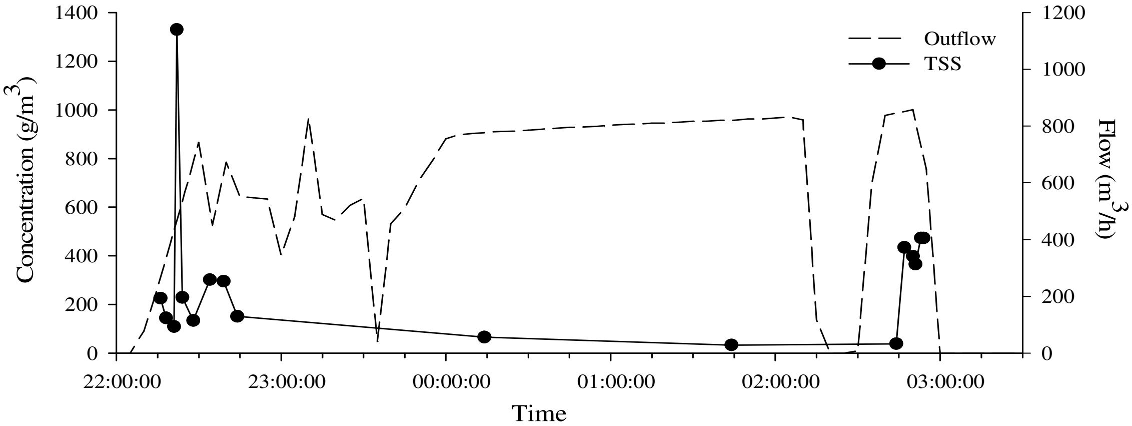

Figure 1. Typical U-shape TSS concentration during emptying of the RT (June 6th 2010).

The TSS concentration profile of the emptying waters is described by:

- **Initial peak:** this peak mostly occurs within the first 15 minutes. The maximum concentration peaks as high as 21000 g/m^3 but is generally around 1500 g/m^3. The TSS load within that period is around **15%** of the total particle mass pumped during an emptying phase. This mass can be traced back to particles that are left behind in the pump chamber after the previous event.
- **Middle phase:** the concentration is nearly constant, around 70 – 80 g/m^3 for each event. Some higher values were observed and correspond to a time when road works were taking place within the catchment area. Water pumped to the WWTP during that phase is the clarified volume resulting from settling within the storage tank. This phase accounts for **70%** of the total mass of an emptying phase.
- **Final peak:** this peak is due to the cleaning system that is washing the settled particles to the pump chamber. The maximum concentration can reach up to 1900 g/m^3 but is more often around 500 g/m^3. That particulate matter is associated with the current event and represents around **15%** of the total mass pumped to the WWTP.

For both the inlet and outlet, Vs distribution analyses were carried out. Averages from 20 ViCAs tests are plotted in Figure 2. The figure highlights the wide range of Vs present. Moreover, **these ranges are linked to a specific phase** (initial, middle and final phases on Figure 2b).

At the inlet, Figure 2a reveals that, for waters sampled within the concentration peak (first flush) produced by the wash-off on the catchment, the mass of particles with a Vs of less than 1.6 m/h is 40%. If a settling velocity of 1.6 m/h is considered for primary clarifier design (Metcalf and Eddy, 2003), it means that 40% of the particle mass won't settle in such a clarifier. For samples taken after the peak, this percentage rises to 80%, hence 80% of that mass will pass such a primary clarifier.

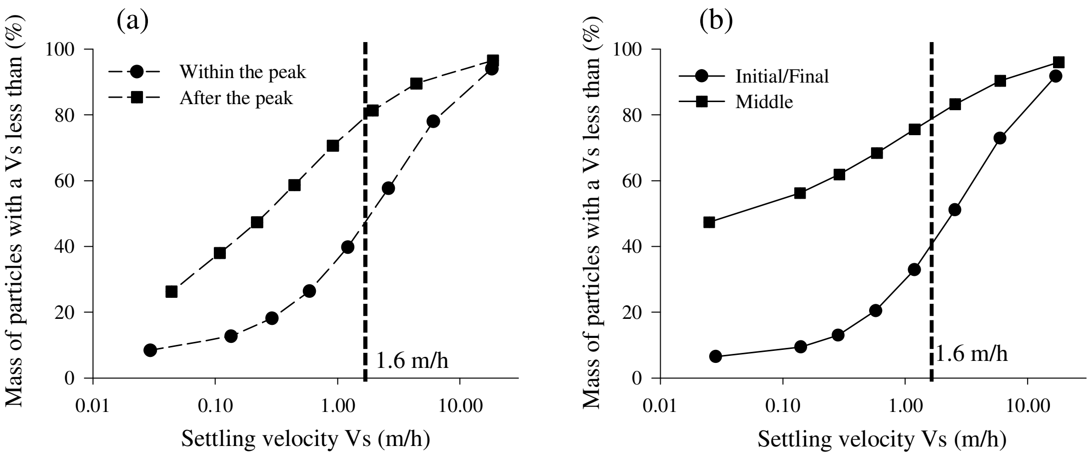

Figure 2. Average Vs distributions associated with: (a) inlet waters collected during or after the wash-off peak; (b) the different phases of emptying.

If we compare the inlet «*within the peak*» curve of Figure 2a with the outlet «*initial/final*» curve on Figure 2b, a high degree of similarity is observed. Therefore, particles that come into the RT with the initial peak are sent to the treatment plant both with the cleaning waters during the final phase of the current event and the initial phase of the subsequent event where the sediment accumulated in the pumping chamber is sent out. That is why the Vs distribution observed within the inlet peak is quite similar to the one from «*initial/final*» of the emptying. Since the heaviest particles settle during storage, we expected the Vs distribution curve to be higher in the middle phase, which is confirmed on Figure 2b. Around 75% of the particles mass have a Vs less than 1.6 m/h within that phase. Finally, curves from Figure 2a are useful to identify the particle classes to input in the improved model.

RT MODELING

The Lessard and Beck (1991) RT model was modified in three steps: (1) starting from a Fortran code, it was first implemented in the wastewater treatment modeling software WEST (Vanhooren *et al.*, 2003); (2) it was then tested with full-scale data to assess its performance and to identify potential improvements; and finally (3) the improved model was tested against the same data.

Lessard and Beck (1991) model implementation

The model was implemented in WEST, software that allows Ordinary Differential Equation (ODE) -based models to be implemented. The Lessard and Beck RT model is based on one-dimensional ODE. It allows simulating settling processes and transport of conservative pollutants (*i.e.* non-settleable COD and VSS, NH_4 or NO_3). The model includes twelve parameters. Equation 1 presents the water mass balance where the change in water volume (V) depends on the difference between inflow (Q_{in}) and outflow (Q_{out}). TSS behavior is represented by two state variables which are the settleable and non-settleable SS concentrations. For each of these fractions, Equation 2 is applied: the change of the concentration in the tank (dC/dt) is a function of inflow (Q_{in}), TSS influent concentration (C_{in}), effluent concentration (C_{out}) and the loss by settling (*Settling*). The settling term only applies to the settleable SS fraction.

$$\frac{dV}{dt} = Q_{in} - Q_{out} \tag{1}$$

$$\frac{d(C)}{dt} = \frac{Q_{in}}{V}(C_{in} - C_{out}) - Settling \tag{2}$$

The model structure includes four flow conditions: filling, storage, dynamic settling (overflow) and emptying. Depending on these conditions, different equations are proposed to describe settling (for more information, see Lessard and Beck, 1991). For verification of the good model implementation, the simulation results obtained by Lessard and Beck were check within WEST and found to agree.

Simulation using full scale data

Results for the simulation of the July 27th, 2009, rainfall event are presented in Figure 3. The volume reached was 4064 m^3 (54% of tank capacity). The pumped outflow is rather constant except for the final phase where a sharp increase is observed. Since also the final concentration peaks occur during this hydraulic peak, the TSS load to the WWTP increases considerably. The volume fraction at which resuspension starts at the end of emptying (parameter *a8* in Lessard and Beck) was fixed at 0.013 which corresponds to the last 100 m^3. Since the emptying is controlled by pumps, the pumped outflow is an input for the model.

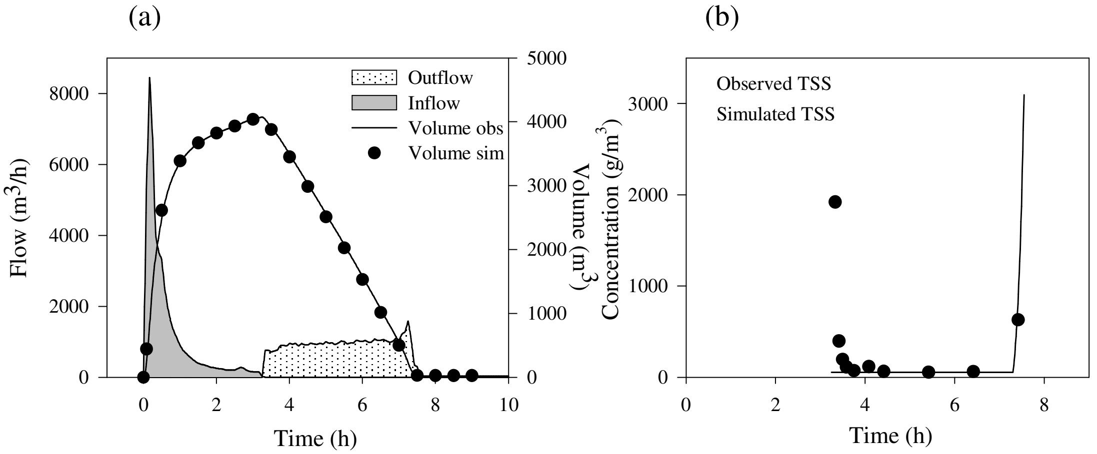

Figure 3. Simulation results for the July 27th, 2009, rainfall event using the model from Lessard and Beck model: (a) hydraulic behavior; (b) outlet TSS concentration.

As expected, the model is able to reproduce the observed hydraulics. Settling is also quite well reproduced by the model: the measured and simulated middle phase concentrations are similar (around 70 mg/l). To reach that value, the particles' removal rate (parameter *a10* in Lessard and Beck) was set to 0.4 h^{-1}. Nevertheless, **the typical U-shape cannot be reproduced, especially concerning the initial concentration peak**. As mentioned earlier, the mass associated with that phase corresponds to the particles remaining in the pump chamber from the previous event.

Model upgrade

In Lessard and Beck, the equations used to describe settling under different flow conditions require various approaches for describing the sedimentation. During dynamic settling, which corresponds to overflow conditions, an average Vs is used while during the other phases the settling velocity is controlled by a first order removal rate constant (h^{-1}). Finding the latter value is not trivial since its physical sense is not clear. On the other hand, Vs can be estimated with reasonable precision. The main improvements to the model focus on: settling equations, adding different particle classes, removing the removal rate parameters, and reproducing the first peak by adding a pump chamber. These modifications will be developed below.

The model scheme of the RT/pump chamber system is shown in Figure 4. It allows the emptying to be controlled by pumps, settling/resuspension processes and transport of conservative pollutants. With regards to TSS concentrations for both the inlet and outlet, one layer was sufficient to reproduce the processes occurring within the tank. No volume needs to be defined for the mass accumulation compartment, since the sludge height is negligible compared to the water height. The RT is hydraulically connected to the pump chamber: the water level is assumed to be the same in both tanks at any time.

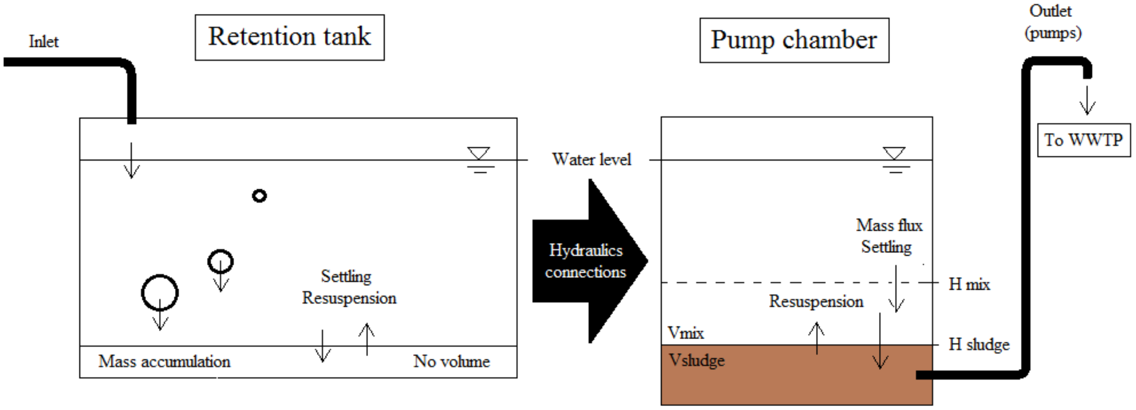

Figure 4. Proposed retention tank/pump chamber model.

The Pump Chamber

The water volume remaining at the end of an event is represented by *Vsludge* (in grey on Figure 4). Through the hydraulic connection, clarified water flows on top of the sediment layer. When the pumps are activated, particles remaining in that volume will be re-suspended according to a first order process. *Vmix* represents the maximum volume influenced by the resuspension. Thus, re-suspended particles cannot go above the *Hmix* height. Dimensions of *Vsludge* and *Vmix* have a direct impact on the concentrations observed at the outlet. The lower *Vmix*, the faster the mass remaining in the pump chamber will be pumped to the WWTP.

Particle classes

Determination of particles classes with different Vs is possible according to ViCAs curves obtained at the inlet (Figure 2a). The model has been developed using three particle classes: 20% of particles with Vs_1 = 0.05 m/h; 60% with Vs_2 = 1 m/h; and 20% with Vs_3 = 5 m/h. The mass balance used to describe the dynamics of the mass of particles of a certain Vs class *j* in the RT is as follows:

$$\frac{d(M_{clar,j})}{dt} = Q_{in}.C_{in,j} - (Q_{out} + Q_{over}).C_{clar,j} - C_{clar,j}.Vs_j.A + k.C_{clar,j}.V \qquad (3)$$

The derivative of the mass of a particle class *j* with respect to time depends on the influent TSS concentration ($C_{in,j}$) and the TSS concentration and mass in the clarified volume ($C_{clar,j}$ and $M_{clar,j}$) for class *j* according to outflow (Q_{out}) or overflow (Q_{over}) conditions. Vs_j is the settling velocity for the class *j*. The last term is a first order equation describing the resuspension process. It depends on a resuspension rate (*k*) and the volume (*V*).

Simulation results and discussion

A simulation has been carried out with the same full scale data as Figure 3a. Hydraulic and TSS results are shown on Figure 5. To obtain these results, the sludge volume (*Vsludge*) and mix volume (*Vmix*) have been set to 25 and 80 m^3, respectively. A quantity of mass had to be added as an initial condition in the sludge volume to represent the mass remaining in the pump chamber from the previous event. It was also found that the particle Vs distribution had to be different from those used for the tank influent, since the matter contained in that sludge volume comes from the settling of the previous event. Those particles are the ones which settle the fastest during storage. After a first run, the mass fraction obtained in the sludge volume can be reused as initial conditions for the simulation of a subsequent rain event. Here, the total initial mass was set to 48 kg and was distributed as follows: 5 kg for the Vs_1 class, 40 kg for the Vs_2 class and 3 kg for the slowest class Vs_3.

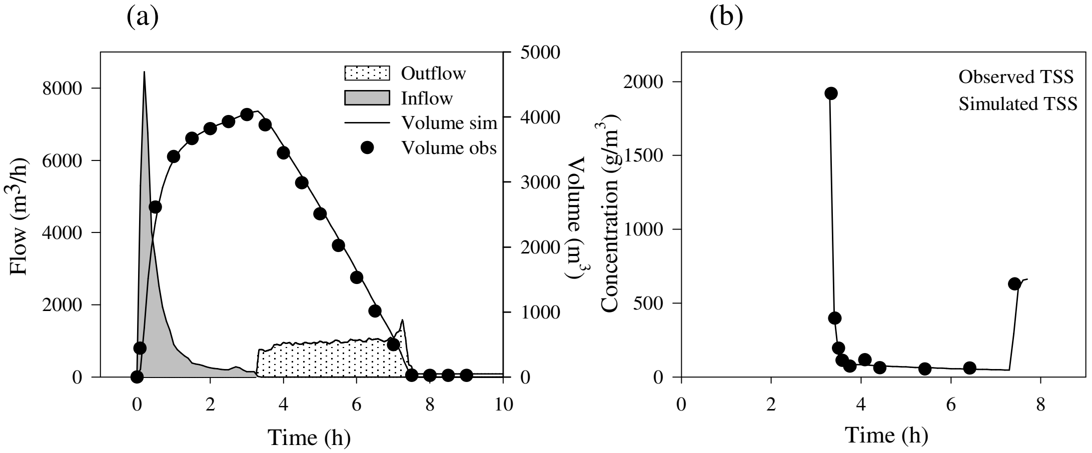

Figure 5. Simulation results for the July 27th, 2009, rainfall event using the improved model: (a) hydraulic behavior; (b) outlet TSS concentration.

The hydraulic behavior is quite similar to Figure 3a even if the pump chamber has been added. The most important change concerns the outlet TSS concentration, resulting in good agreement with the observed data. The maximum value of the first peak is reproduced by setting the initial mass to 48 kg. For future studies, this initial mass should be calibrated and validated using full-scale data sampled during two consecutive events. Sludge and mix volumes might need to be adjusted. Within the middle phase, the observed data show a TSS concentration that is decreasing slowly from 73 g/m^3 to 54 g/m^3. This is due to continued settling during emptying. The simulation results present the same behavior within that phase, decreasing from around 80 g/m^3 to 47 g/m^3. The final peak has been reproduced by adjusting the resuspension parameter (h^{-1}). To estimate the robustness of the model, a validation study needs to be carried out in future.

CONCLUSION

Specific ranges of settling velocity distributions were observed for both retention tank (RT) inlet and outlet. They are linked to the dynamics of the TSS concentration associated with different operating phases of a retention tank, which should thus be taken into account when modeling TSS dynamics. In such a context, the Lessard and Beck (1991) RT model has been improved by integrating information on the Vs distribution as well as settling/resuspension processes occurring in a pump chamber. The improved model has been tested with full-scale data showing its potential. However, more studies are needed to assess its robustness and to correctly estimate the performance gain due to adding different Vs classes. Resuspension processes could be represented as a function of pump activity, enabling the mixing energy induced by the pumps to govern resuspension. It is expected that integrating particle classes with different Vs in models for urban wastewater management will lead to improve model performance and therefore better evaluation of system modifications.

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