A particle settling velocity-based integrated model for dry and wet weather wastewater quality modeling

Thibaud Maruéjouls[1,2], Paul Lessard[1] and Peter A. Vanrolleghem[1,*]

[1]Université Laval, Département de génie civil et de génie des eaux, 1065 av. de la Médecine, Québec, QC, G1V 0A6, Canada (corresponding author: Peter.Vanrolleghem@gci.ulaval.ca)
[2]Suez Environnement, Lyonnaise des Eaux Research Center, LyRE, 91 rue Paulin, BP9, 33029 Bordeaux, France

ABSTRACT

Integrated urban wastewater system modeling is improved by the work presented in this paper by introducing a modeling approach that is based on the fractionation of particle mass in various classes with specific settling velocities. The observation regarding the evolution of the particle settling velocity distribution (PSVD) along the wastewater system and with time can be captured with this model. The model is calibrated by using data that are easily collected with the low-cost ViCAs experimental set-up. A case study consisting of an actual urban catchment, retention tanks, a combined sewer and a pre- and primary treatment is presented. Each subsystem model uses the PSVDM concept. The calibration/validation was successful in showing excellent descriptions of water quality at different places in the case study catchment. The simulations have demonstrated that this PSVD-based modeling approach allows predicting that the concentration of rapidly settling particles in a primary clarifier effluent is increased under wet weather conditions.

KEYWORDS

Particle properties, Sedimentation, Wastewater quality modeling, Wet weather management

INTRODUCTION

Combined sewer overflows (CSO) but more generally, wet weather situations, are an important source of pollution for aquatic ecosystems. Studies have demonstrated that the pollution discharged through CSOs can be larger than by the WWTP effluent, especially for TSS (Brombach et al., 2005) and therefore many efforts are made to reduce wet weather impacts. One of the most common ways consists of building retention tanks (RT) along the sewer system. However, operation of these tanks, especially their emptying, impacts the whole wastewater system. Indeed, emptying in a short time may produce significant disturbances at the plant, while emptying over a long period could lead to more overflows in receiving waters because tanks will not be emptied in time before the next rain comes (Lindholm, 1985). Very few studies have been able to assess the real impact of stormwater management by means of holistic observations on the environment, taking the catchment, the sewer and the WWTP processes into account (Benedetti et al., 2013), but the data requirements are very large (Langeveld et al., 2013). Indeed, the range of issues and conditions is so large that a single measurement campaign may not suffice. Practically, the only feasible way to tackle this topic is to build efficient integrated models aggregating a wide range of knowledge and data from various physical subsystems so that the complex interactions between the subsystems can be studied.

The present study proposes a new calibrated integrated urban wastewater model (urban catchment – retention tank – sewer – primary treatment, Figure 1) based on the innovative particle settling velocity distribution model (PSVDM). The integrated model configuration is inspired by an actual full-scale system, and it is possible to simulate the behaviour of the whole system for a week under wet weather flow (WWF) conditions, in less than 2 minutes.

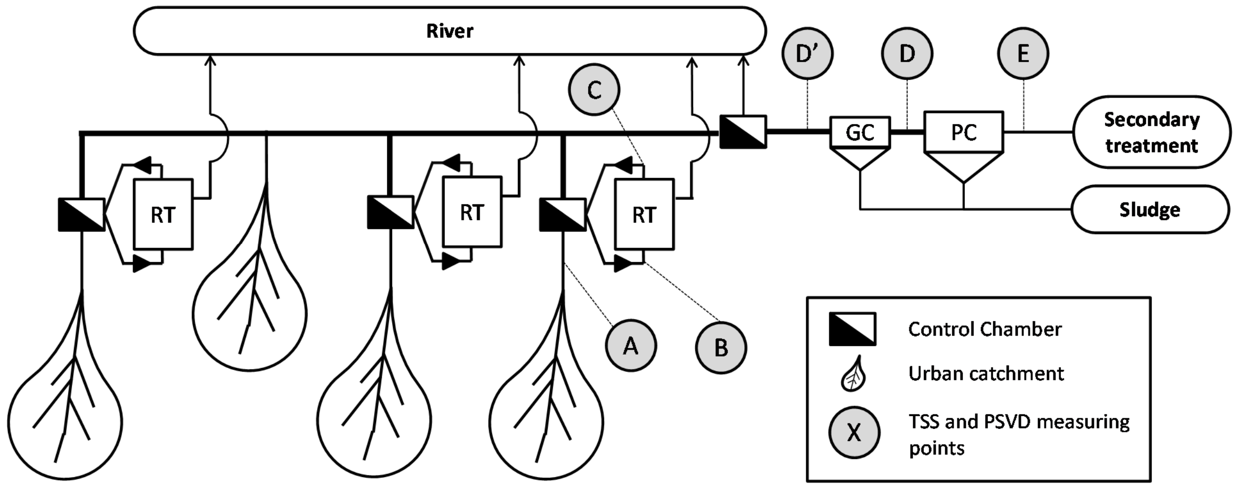

Figure 1. Scheme of the studied integrated system including three controlled urban catchments thanks to off-line retention tanks (RT) plus one uncontrolled catchment, a 3.75 km combined sewer, a grit chamber (GC) and a primary clarifier (PC).

MATERIALS AND METHODS

In situ field data

The PSVDM is based on settling velocity distribution measurements and has been found to only need a few experiments to be calibrated (Maruéjouls et al., 2014a; Bachis et al., 2014). In this work, the ViCAs protocol (Chebbo and Gromaire, 2009) was selected as settling measurement equipment. It consists of a Plexiglas column containing only 4.5 L of sample in which particles settle in stagnant conditions for 4, 8 or 24 hours depending on the studied system. Settled particles are collected at various time-steps at the bottom of the column, are filtered and weighed. Starting from the accumulated mass curve obtained, TSS fractions having a certain Vs can be estimated thanks to a small Excel solver macro. The final result takes the form of a cumulative distribution curve (PSVD curve) as displayed on Figure 2.

The integrated model is able to better reproduce the total suspended solids (TSS) dynamics than currently existing models, thanks to the use of the particle settling velocity distribution (PSVD). An important factor for this success was that the model is able to reproduce the observation in several sampling campaigns that a considerable variation of the PSVD over time and along the integrated wastewater system occurs.

Figure 2 presents a summary of PSVD results illustrating this variation along the system. One can note that samples at the RT inlet taken under dry weather conditions (A and D), exhibit a “lighter” PSVD than during wet weather conditions (B), but they are “heavier” after the wastewater has settled (C and E). The observations also highlighted that the PSVD was highly correlated with the

TSS concentration of the sample, making that the PSVD evolves with time as does the TSS concentration. As far as the authors know, no study has tried to reproduce this variation in settling properties, although Maruéjouls et al. (2012) and Bachis et al. (2014) both proved the gain of performance that could be achieved when using the PSVDM concept.

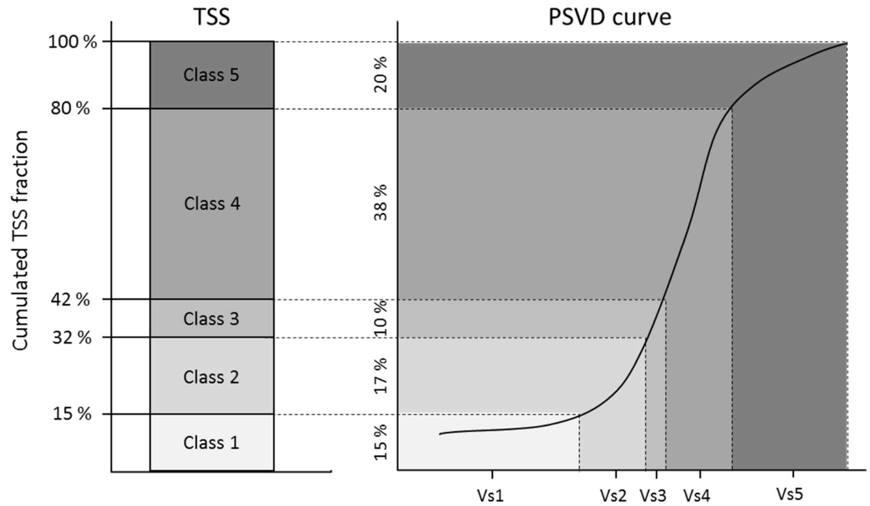

Figure 2. Concept of TSS fractionation from a PSVD curve (measured) necessary to calibrate the model, an example for 5 classes. In PSVDM, a class contains a specific TSS fraction having specific Vs, i.e., here class 1 contains 15 % of TSS that has a Vs of Vs1.

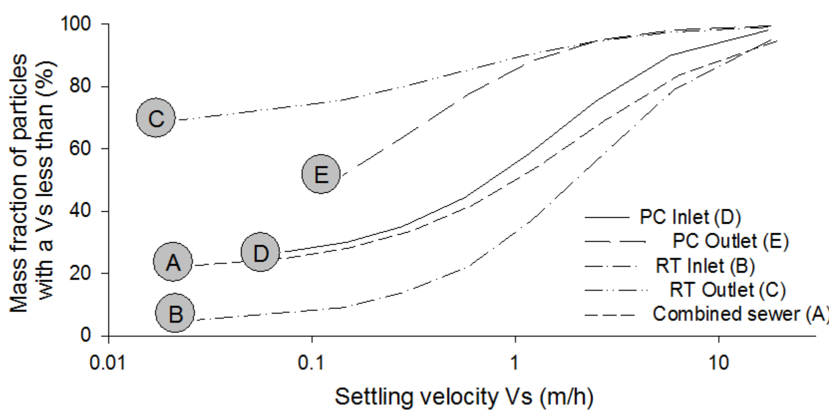

Figure 3. Dynamics of PSVD along the urban drainage system and the WWTP. Capital letters refer to the various locations in the system represented on Figure 1.

Description of the overall model configuration

The integrated model of the case study (Figure 1) consists of three controlled urban catchments thanks to off-line retention tanks plus one uncontrolled catchment. They were calibrated to mimic typical dry weather daily patterns of flow rates and pollution (concentrations and fluxes). Thus, the only model input feeding the simulation is a distributed rain intensity time series obtained from field rain gauges. This rain intensity series is transformed in flow rate and pollutant concentration time series given the many modelled processes including runoff, infiltration, evaporation, retention in soil depressions, surface pollutant accumulation and wash off, etc. Each controlled catchment outlet is equipped with an off-line retention tank (RT) that is emptied by pumping. The recently developed RT model uses particle classes with different Vs (Maruéjouls et al., 2012) and was calibrated and validated against full-scale field data. Each catchment's wastewater is routed to the WWTP through an interceptor that is modelled as a ten tank Nash cascade describing flow propagation and dispersion. The model of this 3.75 km interceptor correctly reproduces the water travel time (1h15) thanks to a calibration using Kalinin-Miljukov's method that only relies on the sewer's structural features (Solvi, 2006). At the WWTP the grit chamber (GC) and the primary clarifier (PC) model are also based on the PSVD-concept, successfully calibrated and validated by Bachis et al. (2014). In the current paper, only the catchment and the combined sewer and primary treatment systems are studied. The secondary treatment modeling concept can be found in Maruéjouls et al. (2014b).

Description of water quality state variables

The catchment model, based on KOSIM-WEST (Solvi, 2006), produces TSS, particulate and soluble COD and NH_4. The way these pollutants are fractionated in the whole PSVDM is presented below. NH_4 remains conservative and is not fractionated. Soluble COD is fractionated in readily biodegradable COD (S_S), inert soluble COD (S_i) as in Activated Sludge Model No1 (ASM1). Each particulate pollutant produced by the urban catchment is fractionated in various particle classes having specified settling velocity Vs before going through the integrated system (Figure 4). Fractionation parameters are noted (f) and separated in two categories: 1) nine ASM1 composition parameters (f_{Xii}, f_{Xs}, f_{Xi}, f_{XBH}, f_{XND}, f_{SNH}, f_{SND}, f_{Si}, f_{SS}) and, 2) n PSVD parameters ($f_{1,2,\ldots,n}$) that are directly linked to PSVD measurements collected in the field and defined with ViCAs experiments.

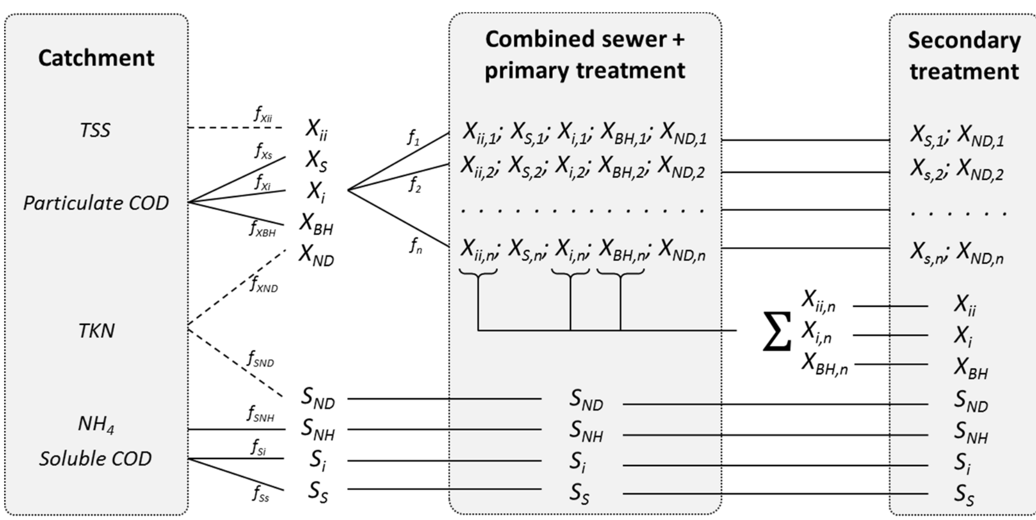

Figure 4. Scheme of the state variables used in each subsystem. TSS and particulate COD (containing nitrogen) are the pollutants to be fractionated, f_n are the fractionation parameters (%) and $X_{ii,n}$, $X_{ND,n}$, $X_{S,n}$, $X_{BH,n}$ and $X_{i,n}$ are the particulate variables of the PSVDM. After the primary clarifier, $X_{BH,n}$ $X_{ii,n}$ and $X_{i,n}$ are summed into a single class. Parameters with continuous lines correspond to fractions while parameters with dotted lines correspond to correlation factors.

A dynamic PSVD

Since the PSVD at a different locations in the wastewater system were found to be highly varying within the day in (linear) relation with the TSS concentration, the parameters of the fractionation model of the particulate matter are changing as well at each time step depending on the current value of the TSS concentration. This works in the following way: for each location along the wastewater system (Figure 1), the measured ViCAs curves can be situated at a certain level (Figure 3) but varying in a certain zone around it. For instance, Figure 5 presents the PSVD zone where the fractionation of particles at the catchment outlet occurs depending on the TSS concentration of the sample. Following a linear equation that correlates PSVD to TSS, a mass fraction is calculated at each time step for each settling velocity class depending on the current TSS value that is in between the TSS_{low} and TSS_{high} values of the PSVD zone at that Vs. The obtained interpolated PSVD (e.g., the black line on Figure 5) lies between the zone boundaries defined by TSS_{low} and TSS_{high}. The latter parameters are to be calibrated based on ViCAs measurements carried out on the studied system.

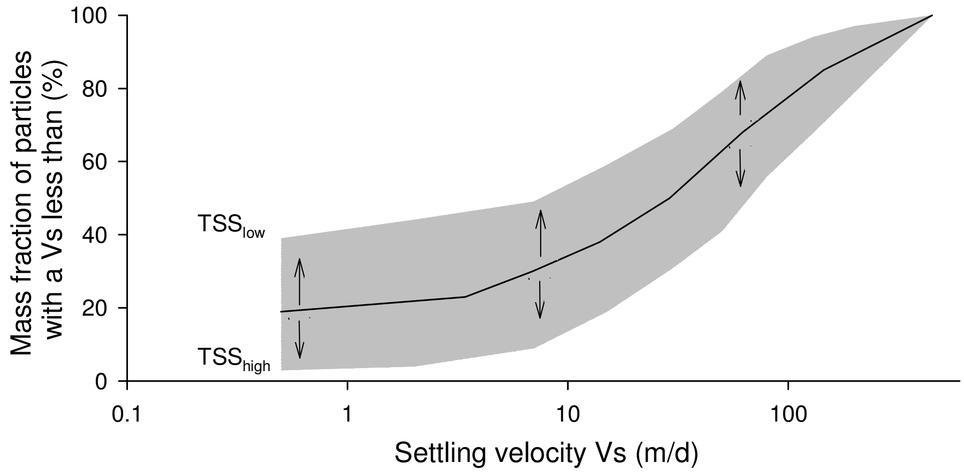

Figure 5. PSVD zone measured in the field at the catchment outlet and used for TSS (A and B on Figure 3). The black curve is the calculated PSVD interpolated between the zone boundaries for a particular TSS. When TSS increases, the curve goes down, and when TSS decreases, the curve goes up.

RESULTS AND DISCUSSION

Hydraulics

Figure 6 presents the hydraulics calibration results comparing the best fitting simulated data (continuous black line) with field data (grey dots) at the WWTP inlet for a period of twelve days. The rain data (model input) and flowrate field data were collected in May after the snow cover had completely melted. From Figure 6, one can clearly distinguish the typical dry weather flow (DWF) patterns (e.g. days 21, 28, 29, 32 and 33) from wet weather flow (WWF). The KOSIM-WEST DWF hydraulics was calibrated based on readily available data such as surfaces, fraction of imperviousness, land use and population density. Four rain events occur within this period with one major multi-rain event (in terms of volume) on days 22, 23, 24 and three smaller rain events on days 26, 29 and 30.

When focusing on the major event, the long-term impact of the rain and the time required to return to the DWF conditions is noteworthy. This “afterglow” can result from a mix of various phenomena such as the retention tanks emptying, rainfall induced infiltration (RII) or the groundwater level variation (Cyr et al. 1990). This observation is more correlated to precipitation volume than precipitation intensity. The model reproduces this delayed inflow quite well. It is to worth mentioning that such results confirm the potential of conceptual models based on Nash cascade theory to model sewer flow propagation in a calculation-friendly way which makes it of great interest for real-time control developments and scenario/sensitivity and uncertainty analyses.

Considering the wide range of uncertainties due to (i) measuring equipment such as rain gauges, flowmeters, (ii) the way of evaluating the soil imperviousness fraction and other model inputs, and (iii) the model assumptions and simplifications, the results of Figure 6 are considered sufficiently good for studying, for instance, real-time control ideas (Tik et al., 2015).

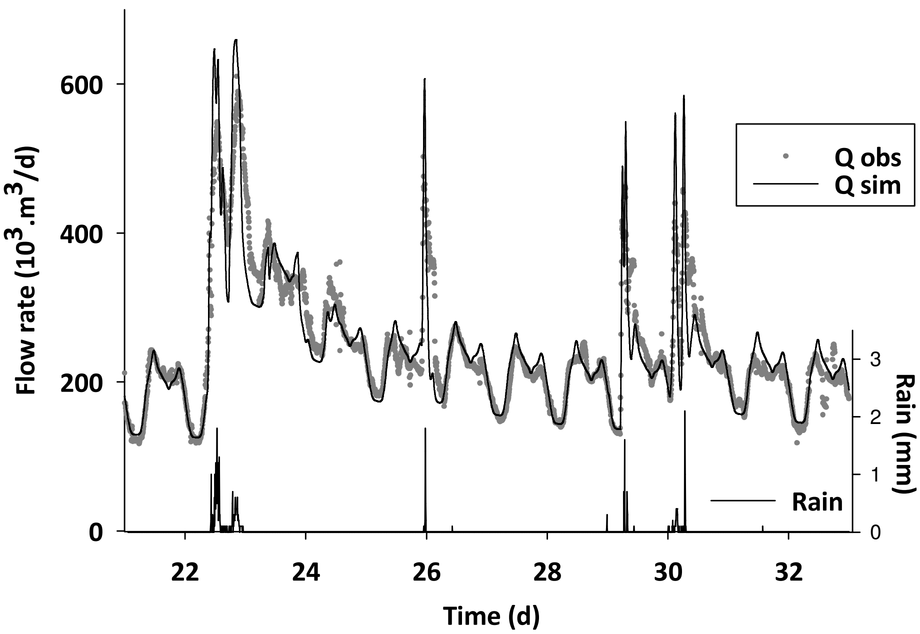

Figure 6. Hydraulics calibration results for DWF and WWF conditions over 12 days of May. Precipitation is plotted as cumulated rain over 5 minutes.

Water Quality - PSVD

The City of Quebec provided daily averaged values for TSS concentrations at the PC outlet in May. The measured values of 65 g/m^3 corresponds very well with the simulated values of 61 g/m^3. These results prove the ability of the integrated model to realistically predict water quality data arriving at the WWTP up to the effluent of the primary clarifier based only on the rainfall time series and a calibration of the household emissions and the catchment properties. Assessment of the quality of the model to deal with the diurnal water quality dynamics is based on the characterization of domestic wastewater quality through three surveys in the United Kingdom (Almeida et al.; 1999). In that study it was shown that a peak TSS load was reached in the morning between 7:00 and 10:00 at around 260 gTSS/100 capita/10 minutes. In the present study, simulations show a similar peak of 250 gTSS/100 capita/10 minutes between 7:00 and 12:00.

Figure 7 shows observed PSVD's at different times during a DW day. The two zones plotted in continuous and dotted lines respectively correspond to GC inlet and PC outlet PSVD's that result from many ViCAs measurements carried out over 3 summer periods (Bachis et al., 2013). The range of simulated fractions of particles having a Vs less than 10 m/d lies between 25 and 35%, while this range is between 25 and 50% for observed field data. The simulation results observed at the the GC inlet show that between 30 and 45% of the TSS mass have a Vs less than 10 m/d, and thus fits in the field data observation zone. Regarding the PC outlet, the simulated range of particles having a Vs less than 10 m/d lies between 55 and 80% for field observations while simulations give a range between 60 and 80%. However, for particles with settling velocities between 20 and 90 m/d, the model and field data differ slightly.

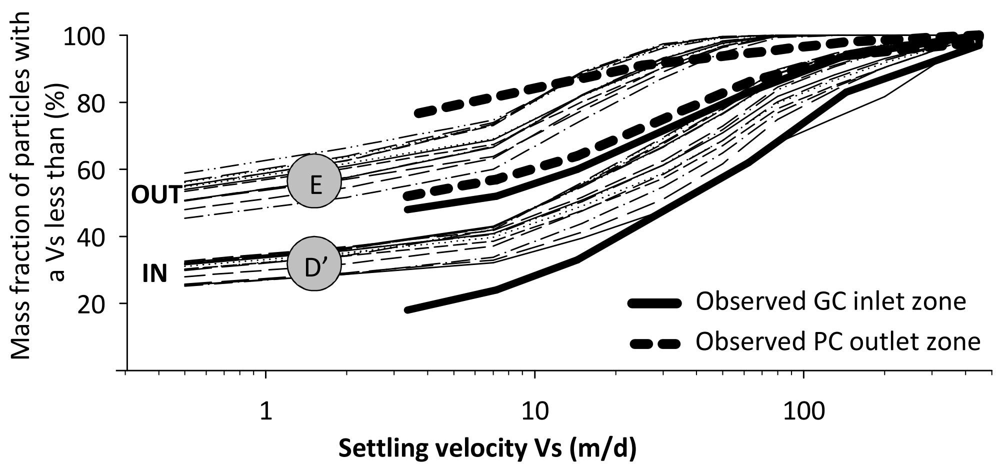

Figure 7. Comparison between simulated PSVD at the inlet and the outlet of the PC (D' and E on Figure 2). PSVDs simulated within a DW day. The continuous line zone includes all ViCAs measurement collected at the GC inlet under DW, while the dotted line zone covers all ViCAs collected at the PC outlet under DW.

Figure 8 presents the performance of the model under wet weather conditions. However, because only a few ViCAs curves were available for WWF conditions, the PSVD zones plotted on Figure 8a and b are the dry weather zones of Figure 7. The plotted simulation PSVD results are the ones simulated for the rainfall event of May 22nd. On Figure 8a the GC inlet PSVD's corresponding to the "first flush" period can be found on the lower part of the graph (indicated with the bracket), while the curves in the upper part of the graph correspond to the end of the rain event. This observation was expected since the "first flush" can mobilize a large quantity of pollutants and thus a large quantity of particles having "large sizes" and high settling velocities arrives at the sampling location during "first flush". The simulation tells us that this large flux of heavy particles coupled with a high hydraulic load at the WWTP entrance has a considerable impact on the effluent PSVD. Indeed, Figure 8b shows a PSVD at the PC effluent that is significantly "heavier" than what is observed under DWF conditions.

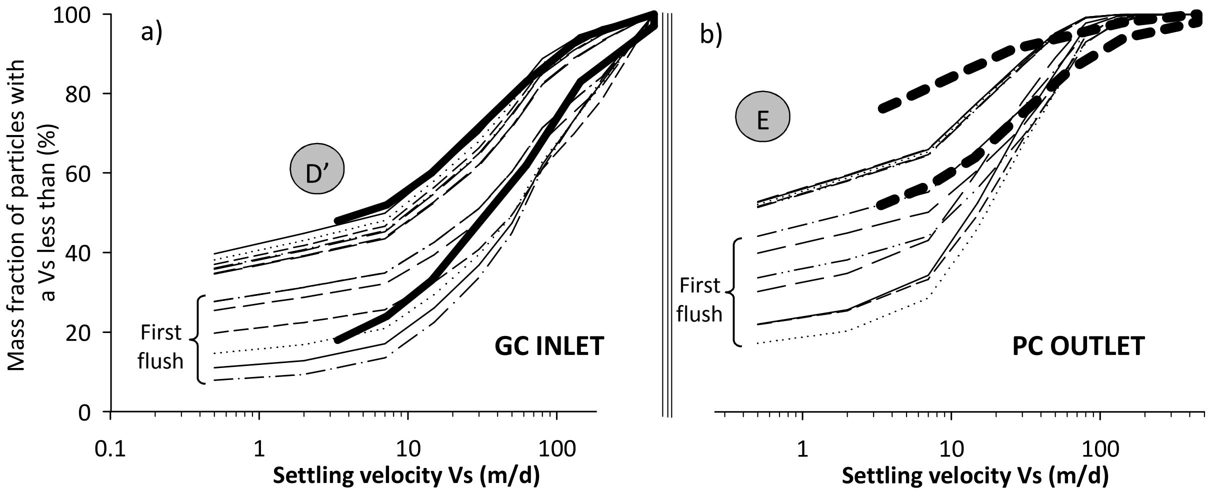

Figure 8. Comparison of simulated WW and full-scale field DW data observations of PSVD: a) at the GC inlet (E) and b) at the PC outlet (D'). First flush samples are indicated with the bracket.

DISCUSSION

It is important to have in mind that the proposed integrated model leads to water quality data that are the result of various processes occurring along the system, such as transport, dispersion, settling and resuspension in the sewer, the RT, the GC and the PC. Particles having various behaviors will be transported differently depending on their settling velocity and the hydraulic regime. The only input data of the model are typical time-varying fluxes of water and pollutants for the DWF situation and time series of rain intensity for WWF. At this moment, the PSVD variation at the catchment outlet is described by an observed correlation between TSS and PSVD. This correlation is based on a model of the particle accumulation on the soil surface and wash-off that relies on the particle's size and density, and thus settling velocity. Indeed, Gaborit et al. (2012) have proven that stormwater runoff water quality modeling performance could be considerably enhanced by fractionating particles into different classes that accumulate and wash-off depending on the rain intensity and their settling velocity, completely consistent with the PSVD model.

Predictions of the PSVD at the inlet and the outlet of the PC show that under wet weather conditions, an increase in particle Vs is found at the outlet of the PC. This is not unexpected of course, but the fact that for the first time such information can be obtained from a model run can be of considerable importance for the management of secondary treatment. Indeed, a number of studies have shown that larger particles (i.e. corresponding to those with higher Vs) are harder to biodegrade (hydrolysis). A model that could also describe such Vs-depending biodegradation kinetics can thus be useful to evaluate the impact of the whole wastewater transport and treatment system on the receiving body, especially under wet weather conditions. Results of overflows and reduction of primary treatment efficiency under wet weather conditions have already been obtained and now the authors are working on the integration of a secondary treatment model that takes PSVD into account so as to better model particle hydrolysis (Maruéjouls et al., 2014b).

CONCLUSIONS

An integrated model that uses particle settling velocity distributions (PSVD) throughout the different unit processes of a wastewater transport and (primary) treatment system to model the fate of particulate pollutants (TSS) was shown to allow fitting simulations and observations and only require a limited number using ViCAs experiments, calibration of the household wastewater generation and catchment properties and rainfall time series. Predictions made with the proposed particle settling velocity distribution model are the result of simulating several phenomena occurring throughout the urban wastewater system such as runoff, pollutant accumulation and wash-off on the urban catchment, settling and resuspension in combined sewer retention tanks, mixing and dispersion in sewers and settling in grit chamber and primary clarifier. Results of the integrated simulations presented in this paper show that it is possible to evolution of the particle settling velocity distribution of the suspended solids as they move throughout the integrated urban wastewater system. It has been proven that such model can bring detailed information on particle behavior along the system allowing for a better prediction of wastewater quality at different locations in the system, but in particular combined sewer overflows and inlet of the secondary stage of the WWTP. RTC strategies can be envisioned on the basis of the improved insights in particle pollution behavior (see Tik et al., 2014). The insights in such PSVD variations can also be of great interest when looking at secondary treatment since few studies have reported the impact of physical properties of particulate pollution (size and settling velocity) on biological degradation or biofiltration (Maruéjouls et al., 2014).

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