A dynamic population balance model for multiple stormwater basin processes

B. Vallet, P. Lessard, G. Pelletier and P. A. Vanrolleghem

Département de génie civil et de génie des eaux, Université Laval
1065 avenue de la médecine, Québec, Qc, G1V 0A6, Canada

ABSTRACT

The presented study is part of a project defining rules for real-time control of stormwater basin outlets to improve the river's water quality, while guaranteeing population safety. The aim of controlling the outlet structure is to increase the water retention time to allow settling of the smallest particles and associated pollutants. The real-time control rules will be defined with an integrated river-catchment-basin model to test a large number of environmental conditions. For that purpose, a new dynamic model for stormwater basins has been developed to describe the water quality dynamics in the basin, independently of the outlet control scenario. This paper is focused on the calibration of the model using total suspended solids data and ViCAs settling velocity distribution data. The latter feed the population of particle classes with different settling velocities. After defining the model, calibration results are presented on two sampled events with open and closed outlet. This model, directly using experimental results for particle settling class description, is able to reproduce both situations. It also describes the spatial heterogeneity in the basin. It is now possible to introduce other processes regarding pollutants associated with particles.

KEYWORDS

Real time control, Sedimentation, Urban wastewater systems, Water quality model.

INTRODUCTION

Stormwater in urban areas can cause serious flooding. At the same time it is known that stormwater contains a considerable amount of suspended solids and associated pollutants (metals, pathogens...) (Characklis *et al.*, 2005; Tuccillo, 2006; Vaze and Chiew, 2004). To deal with flooding, e.g. due to increased impervious area, stormwater basins have been built to reduce hydraulic impacts on the river's morphology and ecology.

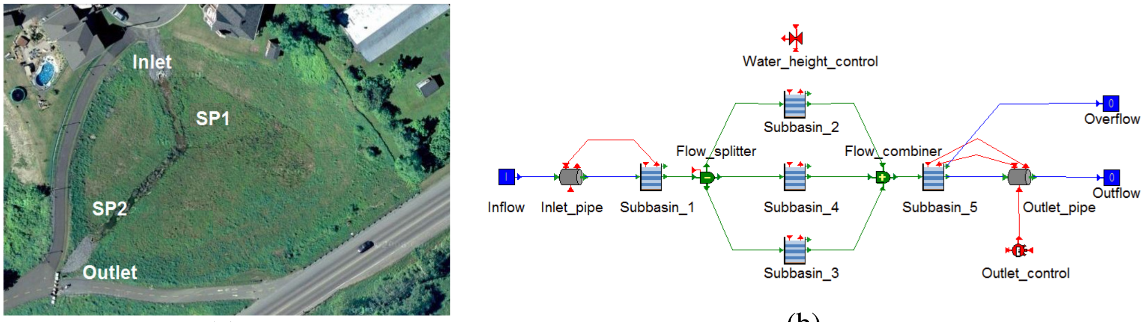
Some earlier studies have successfully tested the idea to equip stormwater basins with sluice gates at the outlet to control the outflow (Jacopin *et al.*, 2001; Middleton and Barrett, 2008) but they have mainly focused on the hydraulics of the basin. The present study is part of a larger project which develops a new approach to improve the eco-hydraulics of the receiving water body (Muschalla *et al.*, 2009). The idea is to implement real time control (RTC) of the sluice gate to enhance the removal efficiency of fine particles by increasing the retention time of stored stormwater and to reduce the peak flow released in the receiving river. An integrated model for the river and drainage system is needed for the safe development of this eco-hydraulic driven RTC of stormwater basins. Robust control rules have to be defined and validated using long-term simulations (Pitt and Clark, 2008) and considering multiple objectives, e.g. flood protection and river water quality. In this context, the quality model of the stormwater basin is key. The computation has to be fast enough to allow long-term simulations. At the same time multiple pollutants (particles, pathogens, heavy metals) and related processes (adsorption/desorption, settling, disinfection) have to be considered to characterise the water quality of the basin's effluent for different environmental conditions.

The aim of this paper is to present the results obtained with the stormwater basin model. It was developed to describe the water quality under varying retention times. It is based on concepts developed in wastewater treatment settler models (Vallet *et al.*, 2010) which are calculating a concentration gradient along the water height by superposition of layers. A central ingredient of the model is the particle population balance with different settling velocities that are experimentally determined by ViCAs experiments (Chebbo and Grommaire, 2009). It is then possible to introduce different processes like chemical adsorption/desorption or light extension for pathogens disinfection (Vergeynst *et al.*, 2010) associated with the different particle classes.

MATERIALS AND METHODS

Sampling campaign

In order to investigate the processes occurring in the basin and calibrate the model, a sampling campaign for two outlet configurations (open and closed) has been conducted on an actual stormwater basin (Figure 1). Flow proportional grab samples of 1L have been taken at the inlet and outlet of the basin. Composite samples have also been collected to perform ViCAs tests. With closed outlet, grab samples have been taken at different points in the basin (SP1 and SP2 on Figure 1.a) to identify the pollutant concentrations during settling. To limit resuspension, a sampling device was designed, allowing the sampler to stay 1.5 m away from the sampling point. The present paper is focused on total suspended solids (TSS) which have been measured according to Standard Methods (APHA *et al.*, 1998). Two events were sampled, one with open outlet (July 11th, 2009; 5.4 mm during 3 hours; I_{max}: 7.2 mm/h on 5 min) and one with closed outlet (July 9th, 2010; 21.8 mm during 2.5 hours; I_{max}: 82 mm/h on 5 min).



(a) (b)

Figure 1: Aerial picture of sampling site (a) and implantation in WEST (b). The 2 sampling points (SP1 and SP2) and the inlet and outlet are presented (a). The channel in the middle of the basin is modeled by the subbasins 1, 4 and 5 (b).

Model implementation

The developed model is based on a superposition of layers as detailed in Vallet *et al.* (2010). It has been implemented in the WEST modelling and simulation software (Vanhooren *et al.*, 2003). This section will not present the equations related to the pollutants' transport but will explain the configuration of the different subbasins and their interconnecting flows' control to allow reproducing the hydraulics of the stormwater basin (Figure 1.b). First, a subbasin is divided in 10 layers and the bottom layer is used as sediment layer, i.e. there is no water transfer from this subbasin to another (Figure 2). Subbasins are connected layer by layer. Particles can be resuspended from the sediment layer with a mixing flow between this layer and the others. In the following paragraphs, objects presented refer to Figure 1.b.

Water Height Controller. The flow Q_{DRAW} out of the different subbasins depends on the inflow, the outflow of the overall stormwater basin and the area of the different subbasins while maintaining the same surface level ($H_{SURFACE}$) for all subbasins.

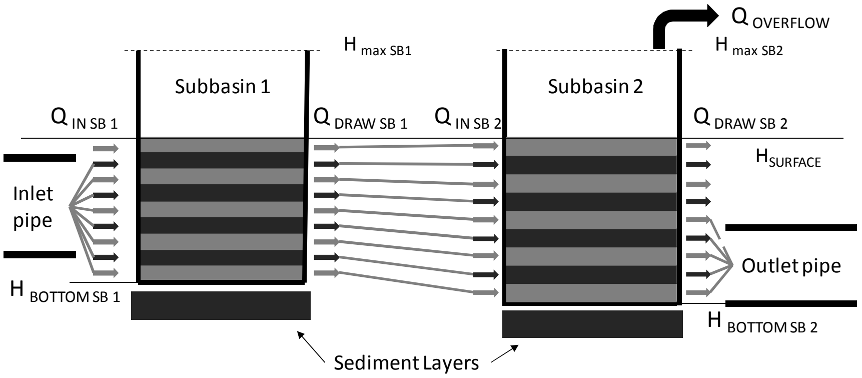


Figure 2: Connection model representation for 2 subbasins.

Inlet and outlet pipe. The role of the inlet pipe object is to calculate the Q_{IN} of each layer of subbasin 1 (Figure 1.b) depending on the position of the surface relative to the inlet pipe diameter. It simply divides Q_{IN} by the number of layers which are below the inlet pipe crown. The role of the outlet pipe object is to determine Q_{DRAW} of each layer of subbasin 5 (Figure 1.b) depending on the position of the surface relative to the outlet pipe diameter. Since a stormwater basin outlet can be considered as a culvert, the outflow is depending on the water height in the basin and on the characteristics of the outlet (Hager, 2010; Smith and Oak, 1995). To take care of the different conditions (outlet pipe submerged or not) and outlet characteristics, the outlet pipe object is using a continuous Hill function (1). Then the outflow is multiplied by a parameter α, representing a controlled sluice gate, and divided by the number of subbasin layers below the outlet pipe crown.

$$Q = \frac{Q_{max} \cdot H^b}{H^b + {H_0}^b} \tag{1}$$

where Q_{max} is the maximum flow in the pipe (m^3/d), H the water height in the basin (m), H_0 (m) the height for which Q reaches $Q_{max}/2$ and b a calibration parameter.

Flow splitter, Flow combiner and Outlet controller. The flow splitter is dividing the flow coming from subbasin 1 depending on the water height in the basin. The flow combiner is just collecting the flow coming from the different subbasins. The outlet controller allows to open and close the sluice gate.

Calibration procedure

For all simulations, the inflow is the result of a calibrated SWMM model of the stormwater catchment. The geometrical characteristics of the different subbasins have been set to fit topographical data. Outflows measured during both open and closed outlet sampling campaigns have been used to estimate the parameters of the outflow pipe equation (1). Subsequently different numbers of particle classes (Vallet *et al.*, 2010) were tested to fit the results of the grab sample TSS data during the sampling campaign with closed outlet. Finally, the mixing flows between the layers were calibrated to reproduce the outlet TSS concentrations in both open and closed outlet sampling campaigns.

RESULTS AND DISCUSSION

Hydraulic calibration

For hydraulic calibration, the area and the bottom height of each subbasin have been set according to the topographical data (Figure 3.a; Table 1). Then the parameters of the outlet pipe connector have been calibrated to have the best possible fit for both the emptying flow for the July 9th, 2010 sampling (Figure 3.b), and for the water height in the basin (data not shown). These parameters are Q_{max} = 30240 m^3/d; H_0 = 0.23 m and b = 3.2. Validation with the open outlet measurements (Figure 3.c) shows that the topographical data are described very well. Since the model has been developed to evaluate the control rules for the outlet sluice gate, it is crucial to simulate the height of water in the basin well.

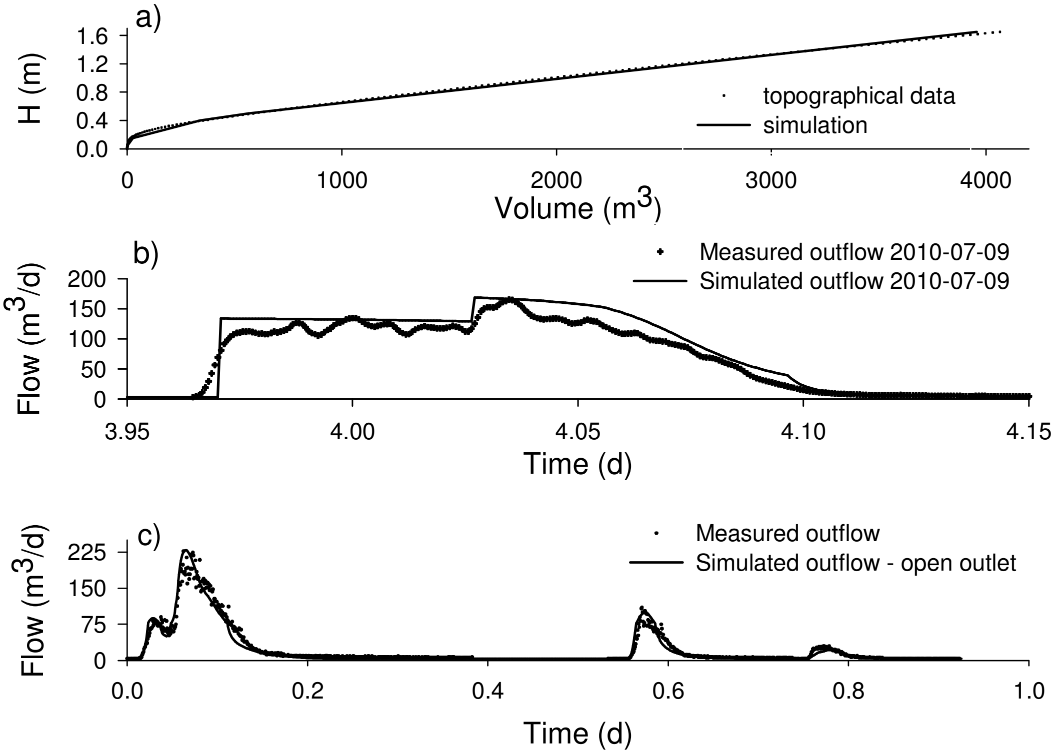


Figure 3: Hydraulic calibration results. Volume and height relationship for topographical data and simulation (a); Flow calibration using the emptying flow after a closed outlet sampling campaign (b) and validation of the outflow for the open outlet time series (c).

Table 1: Subbasin parameters

Parameter	Unit	SB1	SB2	SB3	SB4	SB5
Area	m^2	700	1000	1000	200	50
H_{BOTTOM}	m	0.5	0.4	0.15	0.05	0
$H_{sediments}$	m	0.005	0.005	0.005	0.005	0.005
V_{max}	m^3	798	1240	1480	318	82
Q_{mix_max}	$m^3.d^{-1}$	7000	0	0	7000	1000
K_{mix}	d^{-1}	100	0	0	100	25

Quality calibration

To prepare the input files for the model, ViCAs experiments were used to define the particle settling velocity classes. A ViCAs experiment allows the decomposition of the sample TSS in different fractions associated to settling velocities. Because the ViCAs test was done on an influent composite sample, it was assumed that it is possible to apply this decomposition to each influent TSS measurement of the same event. With this, the input file can be constructed using the particle classes' concentrations as function of time.

In order to develop a model for the TSS associated pollutants, it is important to limit the number of particle classes to keep the characterisation work and simulation speed reasonable (Vallet *et al.*, 2010). Therefore, the first step of the quality calibration was to define the smallest number of classes giving good simulation results. Simulations have been tested for 1 to 5 particle classes. The evaluation of the best number of particle classes was done with the closed outlet event. The particle classes have more influence on that type of invent compared to the open outlet because of the long-time storage of the water. The best results were obtained with 4 classes with characterising settling velocities of 80, 7, 1 and 0.06 m.d^{-1}.

Figure 4 and 5 show two events taken for quality calibration, one with closed outlet and the other with open outlet. On Figure 4 it can be observed that, by dilution and settling of the fastest settling particles, the TSS concentration in the basin is reduced by a factor 10 compared to the inflow concentration peak (a vs b). In the basin, the TSS concentration is higher near the outlet than near the inlet because the first water entering the basin with the peak concentration measured at the beginning of the event is transported quickly through the basin to accumulate at the lowest point of the basin, near the outlet. Note that the settling process allows reaching really low and homogenous TSS concentrations (Figure 54.b). For the open outlet experiment, the inflow and the peak TSS concentration are lower than the closed outlet experiment presented before (Figure 5). Given the relatively low flow particles can settle before reaching the outlet.

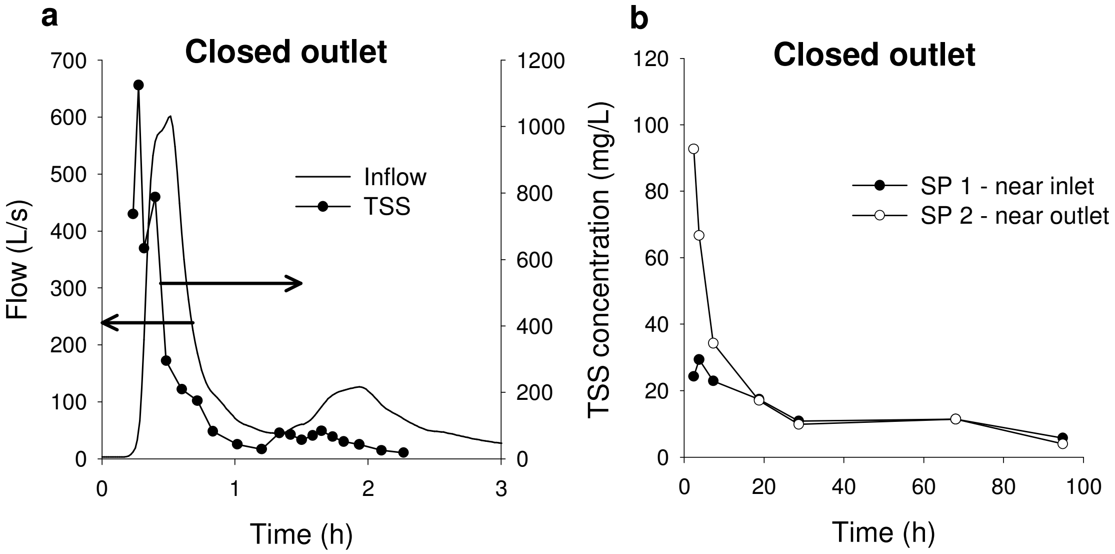


Figure 4: Results for closed outlet event on July 9th, 2010 at the inlet (a) and at two points in the stormwater basin (b). Arrows indicate the axes.

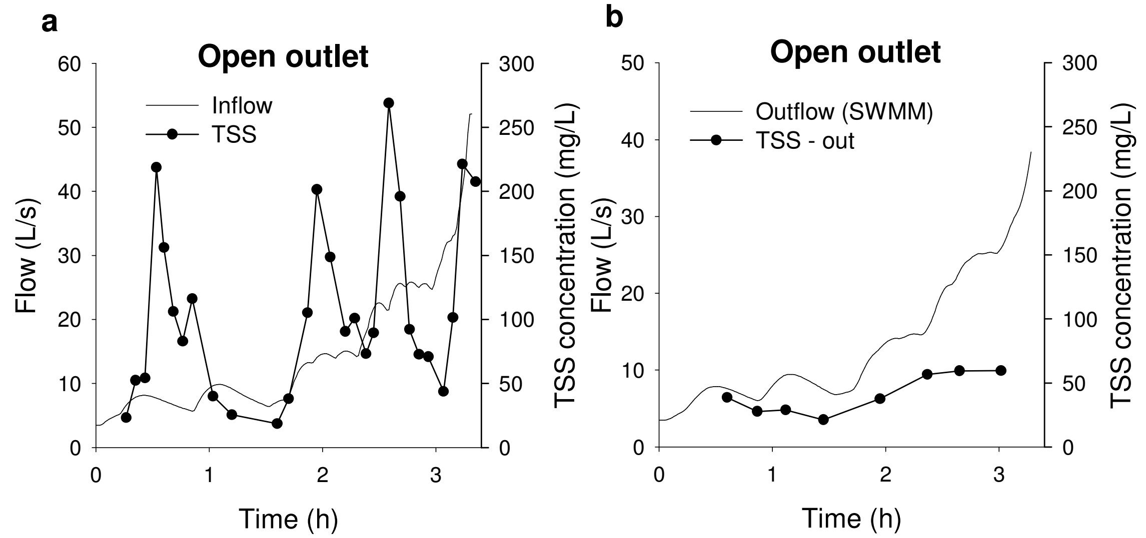


Figure 5: Results for open outlet event on July 11th, 2009 at the inlet (a) and the outlet (b).

On Figure 6 and Figure 7 the simulation results are compared with the data for open and closed outlet events respectively.

Open outlet. Simulation gave good results on the outlet TSS concentration. In this simulation mixing flows around the layers interfaces had to be introduced to allow resuspension of the settled particles. The function used to simulate the inter-layer mixing flow relates it to the inflow of the subbasin Q_{in}:

$$Q_{mix} = Q_{mix\_max} \cdot \frac{Q_{in}/V}{K_{mix} + Q_{in}/V}$$

with V the water volume in the subbasin and Q_{mix_max} and K_{mix} calibration parameters. The calibrated parameters are given in Table 1. With this relation a strong mixing effect can be obtained for small volumes or high inflows. For closed outlet situations too, mixing is decreasing when the accumulated volume is important.

At the beginning of the simulation, it is not possible to reach the first experimental point even considering all pollutants to remain suspended (no settling). Two explanations are possible, i.e. the hydraulics do not allow transporting all pollutants or there is resuspension of previously accumulated sediments. Taking in account the good hydraulic calibration, the second hypothesis seems more realistic. First simulations with an initial mass in the sediment layer gave interesting results but the amount has to be clearly defined which may be problematic on a single event. In long-term simulations with accumulation of sediments during multiple events, this approach could be more promising. It is clear from the above discussion that more work has to be done on the mixing and sediments items.

Closed outlet. Figure 7 shows the simulated TSS concentration in a layer near the surface because the sampling could not be done near the bottom. It can be seen that the model is able to reproduce the water quality for both events, both in the basin and at its outlet. On Figure 7.c, it can be seen that the TSS concentration at the end of emptying increases quickly due to the mixing flow. So far it has not been possible to better describe the outlet TSS concentration with the same mixing flow parameters for both open and closed outlet events. Because the mixing has to be strong in the open outlet configuration and gentle in the closed outlet configuration, further studies are needed.

When comparing Figure 7.a and b, one observes that the two simulations are not really different. This is due to the fact that the samples were always taken near the water surface where the non settling particles remain. However, the modelled concentrations in the different layers show a large heterogeneity along the height of the water column and in the different subbasins. To better calibrate the model, it would be interesting to collect and analyse samples at different water heights. The challenge will be to sample without changing the settling conditions around the sampling point.

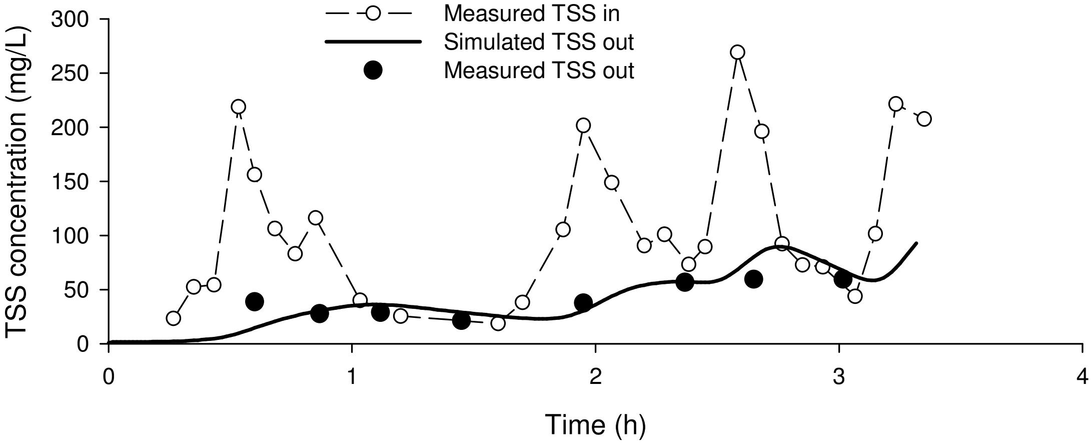


Figure 6: Simulation results for the outflow for the event with open outlet.

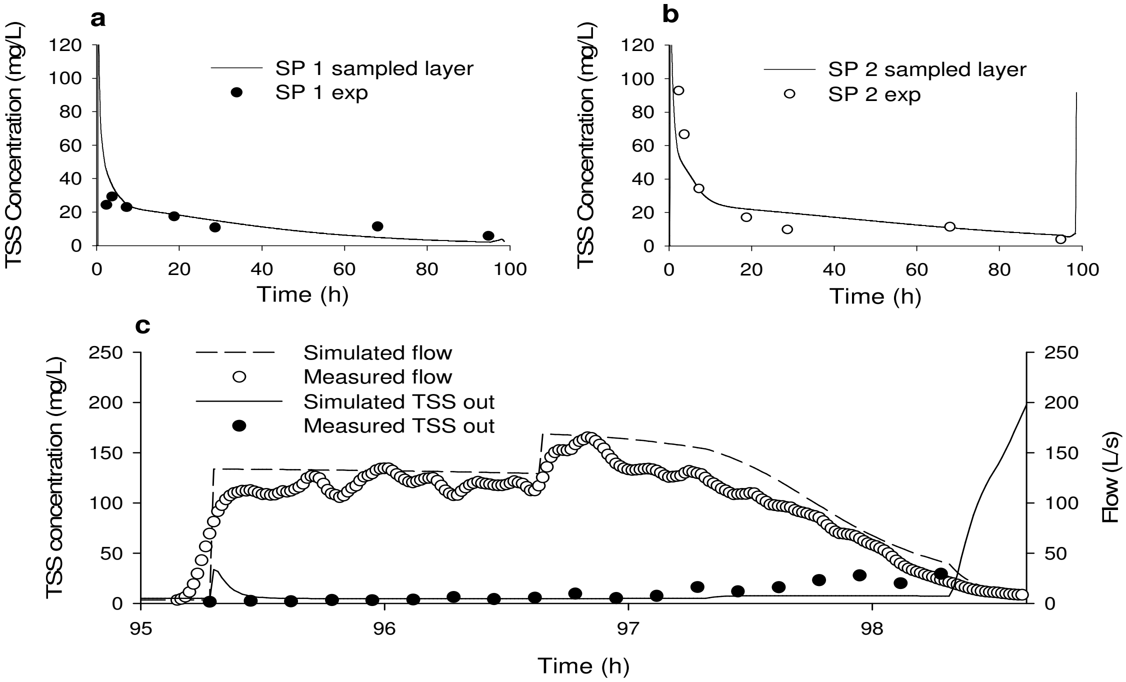


Figure 7: Simulation results for the event with closed outlet in the 2 sampling point in the basin (a and b) and for the outflow (c)

CONCLUSIONS AND PERSPECTIVES

A model was presented that is able to reproduce data obtained from a stormwater basin using a dynamic population balance model. By associating different subbasins that are connected layer by layer to describe the observed hydraulics, and by controlling the outflow, the model is able to reproduce both hydraulic and quality data. It has shown the capacity to simulate the TSS concentration at the outlet of the basin for both open and closed outlet experiments and also to reproduce TSS concentrations inside the basin. Necessary further developments are to improve the mixing flow function to better fit the data with open outlet without creating resuspension at the end of emptying the basin. Multiple pollutants are associated to the different particle classes with different transformations. The model presented in this paper is ready to implement multiple reactions, including phenomena depending on the TSS concentration gradient, e.g. light penetration. This will be the final step before evaluating RTC rules applied on the sluice gate with respect to the reduction of the emissions of TSS-associated pollutants and not only on reducing the emissions of TSS.

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