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A storm water basin model using settling velocity distribution

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Quantifying processes that affect the fate of particles in storm water basins is a complex but necessary step to predict the effect of various pollutants on receiving waters. A dynamic model for storm water basins taking advantage of the experimental fractionation of particles in different settling velocity classes has been developed to describe the water quality dynamics in the basin. This paper is focused on the calibration of the model using total suspended solids (TSS) time series data and settling velocity distribution data obtained from ViCAs (*vitesse de chute en assainissement*) tests. Experimental sampling campaigns have been conducted at an actual storm water basin to identify the TSS behaviour under various operational conditions. For one set of experiments, the outlet was always open, and for another, the outlet was kept closed to allow settling before release to the receiving water. The experimental results reveal spatial heterogeneity of the particle concentrations in the basin during the initial phases of water retention for the closed outlet sampling campaign. A calibration procedure is proposed to fit the model to the experimental data. This model was found able to reproduce both open and closed outlet TSS concentration time series with only three particle classes.

Notation

b	calibration parameter for the Hill function used to compute the outflow
H	water depth
H_0	water depth for which the outflow reaches half of the maximum outflow rate of the basin
H_{bottom}	height of the bottom of a subbasin
H_{sediment}	height of the sediment layer
h_{c}	height of the outlet pipe crown
h_i	position of the layer interface i
h_{i-1}	position of the layer interface $i-1$
K_{mix}	parameter for computing the mixing flow rate
n	number of layers in the water column of a subbasin
n_{Lc}	number of layers below the outlet pipe crown
Q_{draw}	outflow rate of a subbasin
Q_{in}	inflow rate of a subbasin
Q_{max}	maximum outflow rate in the outflow pipe of the basin
$Q_{\mathrm{mix\_max}}$	maximum mixing flow rate of a subbasin
q_i	outflow from each layer i
V	water volume
V_{max}	maximum water volume in a subbasin

Introduction

Storm water in urban areas can cause serious flooding. At the same time, storm water contains a considerable amount of suspended solids and associated pollutants (metals, pathogens etc.) (Characklis *et al.*, 2005; Tuccillo, 2006; Vaze and Chiew, 2004). To deal with flooding, storm water basins have been built to reduce hydraulic impacts on the river's morphology and ecology. By reducing the discharge flow or closing the outlet for a limited period, it is possible to retain the water inside the basin to stimulate particle settling and, therefore, the removal of the associated pollutants from the water column.

Some earlier studies have successfully tested the idea of equipping storm water 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 was part of a larger project which developed a new approach to improve the eco-hydraulics of the receiving water body (Muschalla *et al.*, 2014). The idea is to implement real-time control (RTC) of the sluice gate, based on precipitation forecasting, to enhance the removal efficiency of fine particles by increasing the retention time of stored storm water and to reduce the peak flow released to the receiving river. The finest particles have been found to contain the highest mass fraction of attached pollutants because of their large specific area (Sansalone and Buchberger, 1997).

An integrated model for the river and drainage system is needed for the safe development of this eco-hydraulics-driven RTC of storm water basins. Robust control rules have to be defined and validated using long-term simulations (Pitt and Clark, 2008) and considering

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multiple objectives – for example flood protection and river water quality. In this context, the quality model of the storm water basin is central to simulate faithfully the discharged water quality. It has to give good results for the entire range of possible sluice gate positions. 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 by sunlight) have to be considered to describe the evolution of the water quality of the basin's effluent for different environmental conditions. Computational fluid dynamic models are complex and slow (Torres, 2008), but they showed that heterogeneity may exist in the basins. That heterogeneity has further been confirmed experimentally by analysis of sediments (Walker, 2001). Using the continuously stirred tank reactor concept as such (Ferrara and Hildick-Smith, 1982; Wong *et al*., 2006) allows fast calculation but does not include any heterogeneity.

In the present study, a model simple enough to be fast but detailed enough to represent the different zones of sedimentation in a basin has been developed. It is based on concepts developed in waste water treatment settler models which calculate a concentration gradient along the water depth by superposition of layers and mass balance calculations around those layers (Vitasovic, 1989). By combining several interconnected subbasins, the horizontal spatial heterogeneity is dealt with. The main innovation of the model is the fractionation of the concentration of total suspended solids (TSS) in particle classes with different settling velocities that are experimentally determined. This model has already shown its ability to reproduce laboratory experiments in ideal settling conditions (Vallet *et al*., 2014) and the possibility of adding different processes such as chemical adsorption/desorption or light extension for pathogen disinfection (Vergeynst *et al*., 2012) associated with the different particle classes.

The aim of this paper is to present the results obtained with the storm water basin model for an actual storm water basin under real dynamic conditions. The model developments beyond the model presented by Vallet *et al*. (2014) which focus on the horizontal spatial heterogeneity of the basin are first presented. Then, experimental results collected both within the basin and at its outlet are described before discussing the calibration of the model on these observations.

Materials and methods

Sampling procedure

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 storm water basin (Figure 1). The catchment is a 15·1-ha residential area (Figure 1(a)). In its normal use, the storm water basin is a dry detention pond with a channel in the centre to drain low flows to the river.

During rain events with open outlet configuration, 1-litre flow-proportional grab samples were taken at the inlet and outlet of the basin. Composite samples have also been collected to perform ViCAs (*vitesse de chute en assainissement*, French for settling velocity in waste water treatment) (Chebbo and Grommaire, 2009) tests. A ViCAs test consists of collecting particles that have settled at the bottom of a 60-cm column in a series of aluminium cups and at predefined time steps. The cups with particles are dried and weighed to measure the cumulative mass settled over the duration

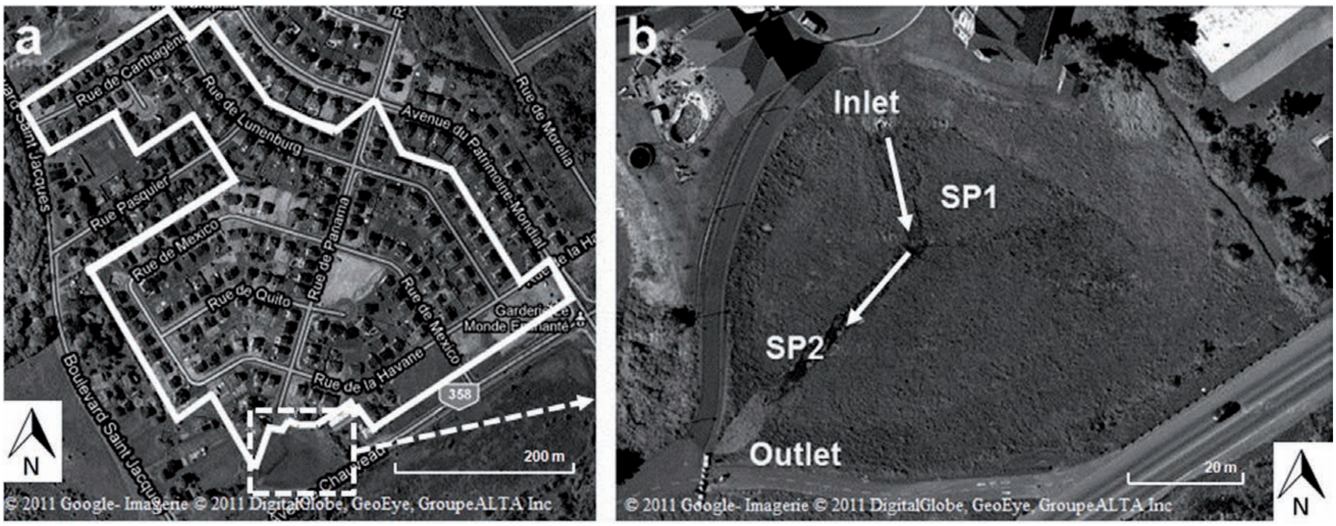

Figure 1. Aerial picture of (a) sampling site and (b) sampled basin. The two sampling points (SP1 and SP2) and the inlet and outlet are presented. The location of the basin in (a) is marked by the dashed-line square. The arrows in (b) represent the normal flow path. © 2011 Google Imagerie © 2011 DigitalGlobe, GeoEye, GroupeALTA Inc

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of the test. The mathematical treatment of this cumulative mass allows obtaining a cumulative frequency distribution curve of settling velocities for the TSS concentration of the original sample. The composite sample for the ViCAs was made by collecting 1-litre grab samples into a 25-litre bucket. The frequency of grab samples was adapted visually to the flow rate. This protocol was selected to be able to collect all types of particles, in particular the bigger ones that could be difficult to catch with an automatic sampler. For the present study, the ViCAs tests were conducted for 2 d with eight to ten different time instances when the settled mass was collected.

In the experiment with closed outlet, the inflow of the basin is sampled in the same way as in the experiments with open outlet. During the rain event, the water accumulates in the pond. After the end of the rain event, the water is kept in the basin for several hours to allow particles to settle. In order to characterise the settling process in the basin, 1-litre grab samples were taken in the water column at different points in the basin (SP1 and SP2 in Figure 1(b)) and at different times after the end of the rain event. The main objectives of these samples were to identify both the pollutant concentrations during settling and the possible spatial heterogeneity of pollutants in the basin. These samples were taken by a person walking in the filled basin up to the sampling points. To limit resuspension due to the person's movement, a sampling device was designed, allowing the person sampling the stored storm water to stay 1·5 m away from the sampling point. To evaluate the effect of settling in time, sampling was performed approximately every 2 h during the first 10 h following the end of the rain event when the fast settling of bigger particles occurs. After 10 h, the frequency was lowered as the settling effect was decreasing. For more details on the sampling campaign, please refer to Carpenter *et al*. (2014). The scope of the paper is limited to pollution characterised by TSS. These have been measured according to standard methods (Apha *et al*., 1998). Whereas multiple rain events were sampled, the results of only three rain events are reported here, in view of modelling purposes, two with open outlet and one with closed outlet (Table 1). The antecedent dry weather period was defined according to the measurement of a rain gauge located at the basin that allowed measurement of the time between two subsequent events with a minimum rain depth of 0·5 mm.

Catchment model implementation

The catchment (Figure 1(a)) was modelled with Storm Water Management Model (SWMM) 5.0 (EPA, 2008). Data on geography, land use and geometry of the sewer systems were available in high spatial resolution and quality. This enabled the development of a detailed model to characterise the hydraulic behaviour of the catchment. The SWMM model has been calibrated on the outflow measurements of the storm water basin (Vallet, 2011).

Storm water basin model implementation

The developed storm water basin model (Figure 2) has been implemented in the Wastewater Treatment Plant Engine for Simulation and Training (WEST) (Mike Powered by DHI Client Care, 2016) modelling and simulation software (Vanhooren *et al*., 2003), a software dedicated to waste water treatment plant modelling and with extensions to storm water and receiving water systems. To describe the vertical TSS concentration profiles in the basin, the model is based on a superposition of layers as detailed by Vallet *et al*. (2014). This section will not present the equations related to the pollutants' transport, as this was already presented by Vallet *et al*. (2014), but it will explain the configuration of the different subbasins and their interconnecting flows to allow the hydraulics and horizontal spatial heterogeneity of the storm water basin to be reproduced.

First, a subbasin is divided into ten layers and the bottom layer is used as sediment layer – that is, there is no water transfer from this sediment layer to another sediment layer in another subbasin (Figure 3). The depth of the sediment layer has been set to 0·005 m for all subbasins. This parameter value was calibrated to have a high concentration of particles in the sediment layer. This permitted the simulation of the effect of resuspension in the upper layers well. There is no direct relation to the actual size of the sediment layer in the basin. For the nine other layers, the subbasins are connected layer by layer, allowing advective flow between them. Particles can be resuspended from the sediment layer with a mixing flow between this layer and the others. This mechanism allows particles of the sediment layer to be transported to a subsequent subbasin under certain conditions. In the following paragraphs that describe the model in greater detail, the mentioned objects refer to Figures 2 and 3.

Water depth controller

The water depth over the overall storm water basin is determined by a 'controller' that ensures that the water depths are coherent. The flow Q_{draw} out of the different subbasins depends on the inflow, the outflow of the overall storm water basin and the area of the different subbasins while maintaining the same surface level (H_{surface}) for all subbasins.

Date	Total depth: mm	Duration: h	Maximum intensity for 5 min: mm/h	Antecedent dry weather period: d	Outlet configuration
11/07/2009	5·4	3·0	7·2	2·8	Open
18/07/2009	22·6	2·5	48·0	0·0	Open
09/07/2010	21·8	2·0	82·0	2·6	Closed

Table 1. Characteristics of sampled rain events

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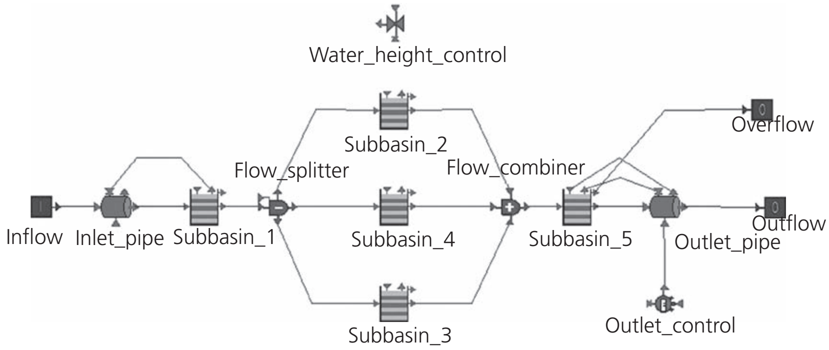

Figure 2. Implementation of the storm water basin in WEST. The channel in the middle of the basin (see Figure 1(b)) is modelled by subbasins 1, 4 and 5

Inlet and outlet pipe

The role of the inlet pipe object is to compute the Q_{in} of each layer of subbasin 1 (Figure 2) 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 as illustrated in Figure 3. The role of the outlet pipe object is to determine Q_{draw} for each layer of the final subbasin (in the example of Figure 2, subbasin 5) depending on the position of the surface relative to the outlet pipe diameter. The inlet pipe distributes the inflow equally to all layers below the inlet pipe crown. The outlet pipe is defining Q_{draw} for each layer depending on the position of the surface relative to the outlet pipe diameter. All layers above the outlet pipe crown have a null Q_{draw}. The layers below the outlet pipe crown have the same Q_{draw}, and the layer around the outlet pipe crown has a fraction of the other Q_{draw}. The sum of all Q_{draw} values is the outflow of the storm water basin.

Since a storm water basin outlet can be considered as a culvert, the outflow depends on the water depth in the basin and on the characteristics of the outlet (Hager, 2010; Smith and Oak, 1995). To account for the different conditions (outlet pipe submerged or not) and outlet characteristics, the total flow from the outlet pipe object is calculated using a numerically efficient continuous Hill function

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

where Q_{max} is the maximum flow in the pipe (m^3/d), H is the water depth in the basin (m), H_0 (m) the depth for which Q reaches $Q_{max}/2$ and b is a calibration parameter. The values of the parameters Q_{max}, b and H_0 have to be calibrated from experimental data. Then, the outflow is multiplied by a parameter α, representing a controlled sluice gate. The outflow from each layer i, q_i, is calculated by

$$q_i = \begin{cases} 0 & \text{if } h_i > h_c \\ \dfrac{Q}{n_{Lc}} & \text{if } h_i < h_c \\ \dfrac{Q}{n_{Lc}} \dfrac{h_c - h_{i-1}}{h_i - h_{i-1}} & \text{if } h_i < h_c < h_{i-1} \end{cases} \tag{2}$$

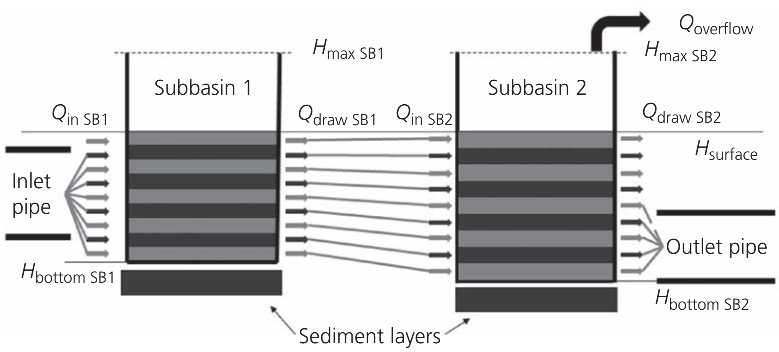

Figure 3. Connection model representation for two subbasins. The number of layers is the same for all subbasins. Two subbasins are connected layer by layer except for the sediment layer

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where n_{Lc} is the number of layers below the outlet pipe crown, h_c is the height of the outlet pipe crown, h_i is the position of the layer interface i and h_{i-1} is the position of the layer interface $i-1$.

Flow splitter, flow combiner and outlet controller

The flow splitter object divides the flow coming from subbasin 1 over the connected subbasins depending on the water depth in the basin. The flow combiner object just collects the flow coming from the different subbasins. The outlet controller allows the sluice gate to be (partially) open or closed.

Model calibration procedure

For all simulations related to the storm water quality model (Figure 2), the inflow was provided by the calibrated SWMM catchment model and the inlet TSS concentrations were provided by the sampling campaign. The calibration procedure is presented in Figure 4. First, a configuration with multiple subbasins is defined. Second, the geometrical characteristics of the different subbasins are set to fit topographical data. Outflows measured during both open and closed outlet sampling campaigns are then used to estimate the parameters of the outflow pipe equation (Equation 1). Subsequently, different numbers of particle classes (Vallet *et al.*, 2014) and

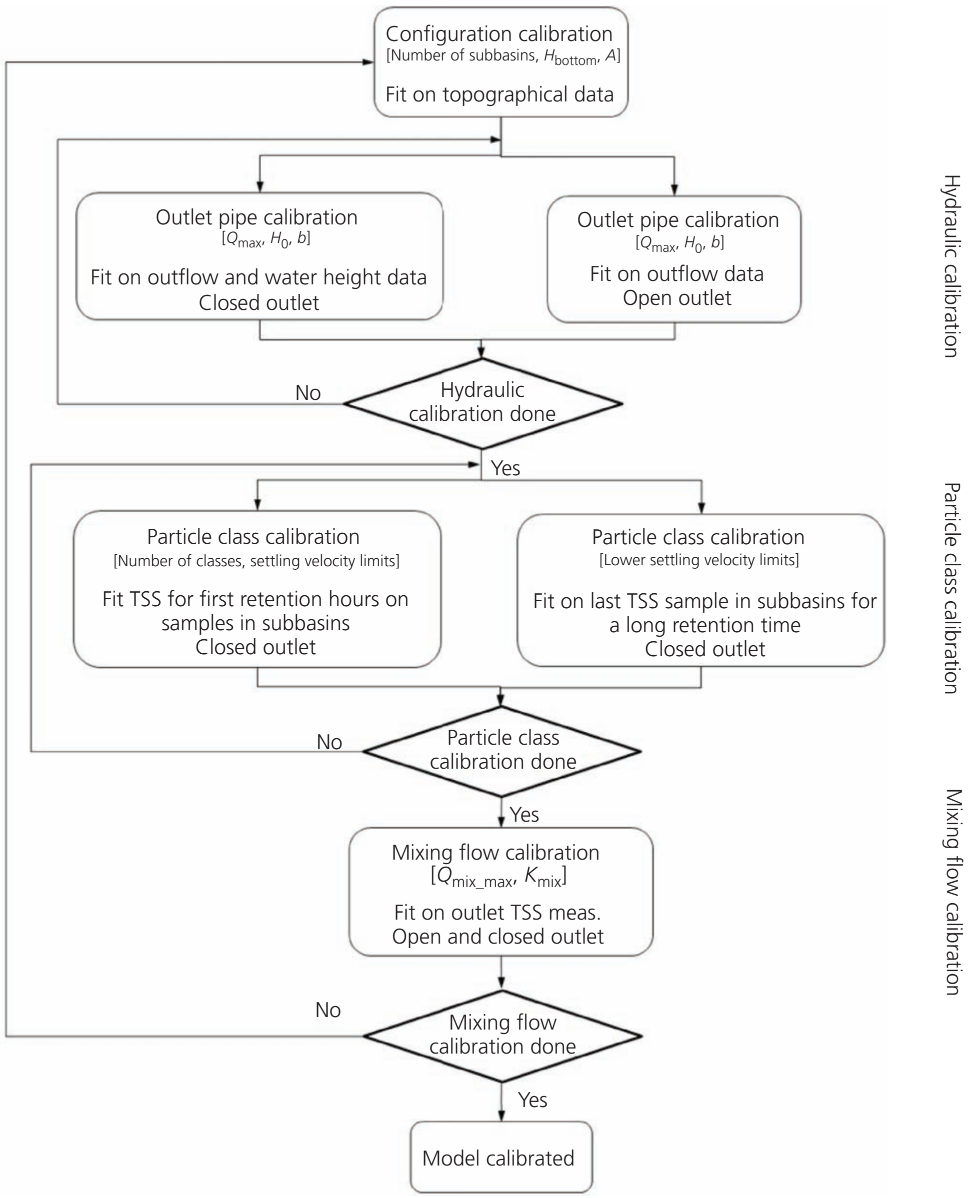

Figure 4. Flowchart of the calibration process. Parameters to calibrate are presented in squared brackets

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velocities are tested to fit the results of the TSS data sampled in the basin (points SP1 and SP2, Figure 1(b)) during the closed outlet sampling campaign. The choice to calibrate the settling characteristics of the model on closed outlet was motivated by the longest retention time that will lead to greater settling. To calibrate the model in order to have a good fit of the data all along the retention of the water in the basin, it is crucial to fit the data on the events with closed outlet rather than the settling with open outlet (for more details on the calibration process, refer to Vallet *et al*. (2014)). Finally, the mixing flows between the layers were calibrated to reproduce the outlet TSS concentrations in both open and closed outlet sampling campaigns. If the simulation results cannot fit the data after this final step, the first modified parameters are the number of classes and settling velocities. If the results can still not be fitted, the configuration of the subbasins is changed and the whole procedure is repeated until a good fit is obtained.

Results and discussion

Experimental results

A detailed description of the storm water basin removal efficiency was presented by Carpenter *et al*. (2014). The purpose of this section is to describe the TSS behaviour in the storm water basin in view of its modelling. Figure 5 presents typical results obtained during the closed outlet sampling campaign. The inlet TSS concentration (Figure 5(a)) shows a strong variation reaching a peak of 1125 mg/l at the beginning of the event, decreasing below 100 mg/l after 50 min. When the TSS concentrations of the sampling point near the inlet and near the outlet (Figure 5(b)) are studied, it becomes clear that they are different during the first 20 h of retention. This difference can be explained by the movement of the water in the basin. The outlet of the basin, initially dry, was closed just before the run-off started. Then, water entering the basin at the beginning of the run-off, which has the higher TSS concentration, is flowing quickly through the basin and accumulates near the outlet. Water keeps accumulating in the basin all along the event. At the time of the first samples in SP1 and SP2, the mean concentration in the basin is 287 mg/l. Through dilution and settling, the concentration decreases quickly from 1000 to 100 mg/l (Figure 5(a) against Figure 5(b)), becoming very similar at both sampling points after 20 h. The final volumes of run-off water are stored near the inlet with a TSS concentration close to the last inflow, which is very diluted. At the end of the basin filling, the settling process favours the decrease in the TSS concentration to decrease in the basin. After around 20 h, the TSS concentration is basically homogenous in the basin.

Depending on the storage time and the absence of a new event, particle settling can lead to really low concentrations. This typical event exhibits spatial heterogeneity in the basin in terms of TSS concentration (Figure 5(b)), at least during the first retention hours. During the last 30 h, the TSS concentrations for both sampling points do not change a lot, but the last points are again lower. Given the experimental uncertainty related to both sampling and laboratory analysis, it can be stated that a continuous decrease in TSS occurs during the 95 h of water retention. Measurement errors were evaluated to be 5% for concentrations above 60 mg/l, 20% between 60 and 10 mg/l and 35% below 10 mg/l. The observed TSS dynamics mean that local processes affected by TSS concentration, such as light penetration and disinfection (Vergeynst *et al*., 2012), will be affected by the observed differences. Also, if the basin outlet is opened during the first hours, the impact of the different TSS concentrations on the receiving water body could be different. This analysis thus allows the conclusion that it is necessary to be able to reproduce this phenomenon with a storm water basin quality model.

Calibration results

Hydraulic calibration

CATCHMENT MODEL

The water depth measurement in the inlet pipe was not available for hydraulic calibration due to installation limitations. It was therefore not possible to use inflow measurements as input for the storm water basin model. Consequently, by using rain gauge data as input

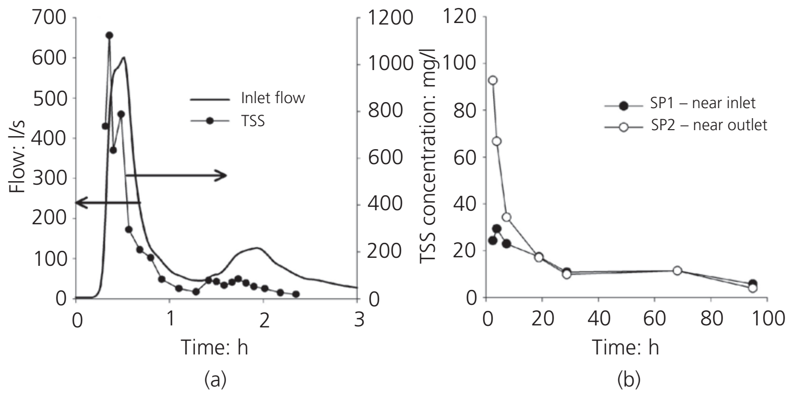

Figure 5. TSS and flow measurements for the 9 July 2010 closed outlet sampling campaign. Inflow and inlet TSS concentration and TSS measurements of grab samples in the storm water basin during 95-h retention for two sampling points, (a) one near the inlet (SP1) and (b) one near the outlet (SP2). The water depths were 49 and 59 cm for SP1 and SP2 respectively

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and topographical data for the storm water basin shape description, a SWMM model of the catchment and the storm water basin was calibrated by using the storm water basin outflow measurements of three events (Figure 6(a)). The corresponding SWMM inflow simulations were then used as input for the developed model.

STORM WATER BASIN MODEL

A configuration with five subbasins was obtained after multiple iterations of the calibration procedure. The particularities of this configuration allow limiting the pollutant mass that was available for resuspension, a necessity for the proper fitting of the TSS data obtained for the 9 July 2010 event (detailed results in the following paragraphs). The subbasin areas and bottom depths were determined using the topographical data to obtain a good correlation between the volume and the water depth of the storm water basin (Figure 6(b); Table 2). The modelled outflow of the basin depends on the water depth, and it is therefore important to model it well. It is also important because the water depth is one of the variables used for the development of the RTC rules (Muschalla *et al.*, 2014).

The experimental outlet structure used to close the basin is rectangular. It thus has a section different from the one of the circular outlet pipe. It means that to be able to calibrate the model for both situations, two different sets of parameters are needed to model the outlet flow–height relationship. The parameters of the outlet pipe connector (Equation 1) have been calibrated to fit the open outlet measurements (Figure 6(a)) considering the maximum designed outflow for Q_{max}. The parameters are Q_{max} = 30 240 m^3/d, H_0 = 0·37 m and b = 2·3. Parameters were also determined for the closed outlet measurements for both the emptying flow of the 9 July 2010 event (Figure 6(c)) and the water depth in the basin (Figure 6(d)). The parameters that fit both data sets well are Q_{max} = 30 240 m^3/d, H_0 = 0·23 m and b = 4.

Water quality calibration

NUMBER OF PARTICLE SETTLING CLASSES AND VELOCITIES

The proposed model uses a TSS concentration for each of multiple settling velocity classes. One original point of the modelling approach is the direct use of ViCAs test results to set the velocity classes (Figure 7). The ViCAs results present the fraction of TSS with a settling velocity lower than V_s, the settling velocity presented on the abscissa. For the example in Figure 7, 60% of the TSS has a settling velocity lower than 10 m/d.

As mentioned before, the pursued characteristics of the model are that it must be fast in computation and that it should consider particle-associated pollutants. Given the first objective, it is then crucial to minimise the number of classes needed. For instance, Figure 7 presents an example of a ViCAs-based fractionation for three classes, with three associated settling velocities (this is the fractionation detail

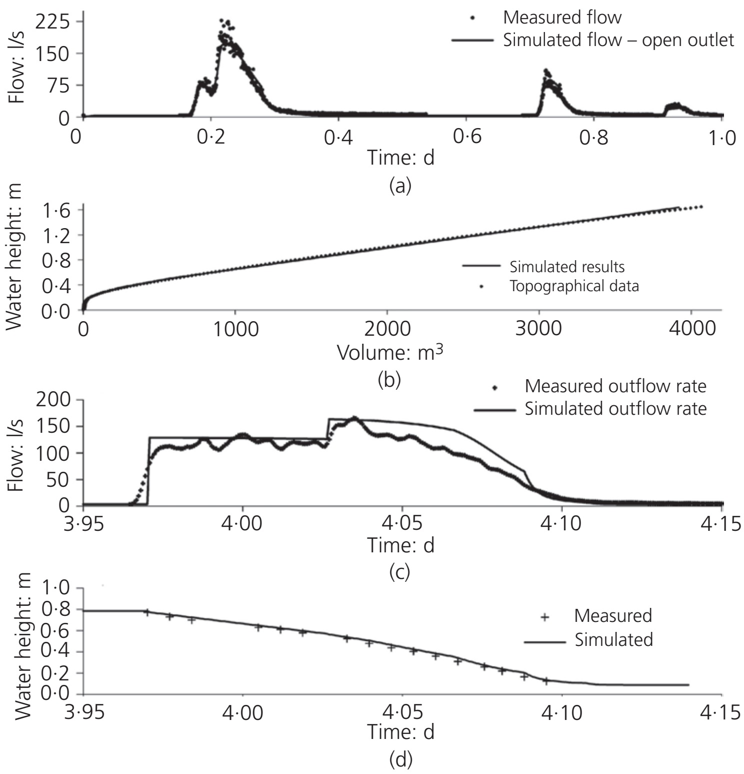

Figure 6. Hydraulic calibration results. (a) SWMM model flow calibration using outflow measurements of three consecutive events for an open outlet sampling campaign. (b) Volume and height relationship for topographical data and simulation. Flow calibration using both the (c) emptying flow and (d) water depth measurements for a closed outlet sampling campaign

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Parameter	Unit	SB1	SB2	SB3	SB4	SB5
Area	m^2	700	1000	1000	200	50
H_{bottom}	m	0·5	0·35	0·2	0·1	0
$H_{sediment}$	m	0·005	0·005	0·005	0·005	0·005
V_{max}	m^3	798	1290	1440	308	82
Q_{mix_max}	m^3/d	10 000	0	0	5000	3500
K_{mix}	d^{-1}	100	0	0	1	1500

Area, H_{bottom}, $H_{sediment}$ and V_{max} of the different subbasins have been set to fit topographical data presented in Figure 6(b)

Table 2. Subbasin characteristics after calibration

that was finally adopted; see the following sentences). The velocity associated with a class is conventionally defined as the geometrical mean between the velocity limits of the class. For the example of the ViCAs results in Figure 7, the TSS concentration is composed of 33% of particles that have a settling velocity of 80 m/d, 56% of particles that have a settling velocity of 2 m/d and 11% of particles that have a settling velocity of 0·1 m/d. Because the lowest velocity measured in ViCAs (0·32 m/d in the example) is high, it will not allow maintaining any TSS in the water column for more than 2 d for most of the events, which accumulate less than 60 cm of water. It is therefore important to reassess the velocity of the last class with the smallest limit (0·03 m/d in the example). This limit is chosen to fit the last observed TSS concentration measurement after a long retention time of the water in the basin (Figure 8(a)).

Once the smallest velocity limit is chosen, the number of classes has to be set. The effect of that number on the results is presented in Figure 8(a). It can be observed that the choice of three classes (continuous line) is better than a choice of two classes (short dashes) with a relative square error (RSE) of 3·5 compared to 11·1. Adding a fourth class (long dashes) did not improve the results.

The next step is the choice of the velocity limits of the classes because many combinations are possible. Changing the velocity limits of the classes changes not only the (geometrical mean) velocities allocated with the class but also the percentage of the TSS concentration allocated to the class. Indeed, by moving the velocity limits, one is also changing the total mass of particles that will settle during the simulation. The simulations for three possibilities of velocity limits (Figure 8(b)) show that the results are really different during the first 5–7 h. According to Figure 8(b)), the best choices for the velocity limits are 80, 2 and 0·1 m/d (RSE = 3·5 against 6·1 and 6). For comparison, the experimental error gives a RSE of 1·0.

Having a representative ViCAs for each event to simulate, it is easy to feed the model with an adapted input file. In the future, it may be interesting to use multiple ViCAs-based velocity distributions to make a more representative description of the different water qualities entering the basin during the event, in particular when it lasts for a long time and the properties of the washed-off particles change. However, in order to use the model for long-term simulations and considering multiple events, it becomes laborious to use an adapted fractionation for each event. Therefore, in this study the same settling velocity limits were chosen for all events. Taking into account the errors in the TSS measurements and in the ViCAs test results (Torres and Bertrand-Krajewski, 2008) and the limited number of classes, the uncertainty given by using predefined settling velocity classes will not affect the simulation results significantly.

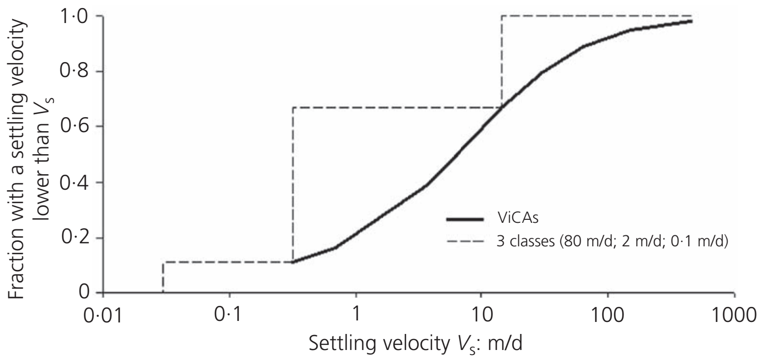

Figure 7. Examples of influent fractionation based on the 11 July 2009 ViCAs curve (black curve). The fractionation is presented for three classes. The velocity associated with a class is the geometrical mean between the velocity limits of the class. The inlet TSS concentration is decomposed in 33% associated with $V_s = (450 \times 14{\cdot}52)^{1/2} = 80$ m/d; 56% associated with V_s = 2 m/d; and 11% associated with V_s = 0·1 m/d

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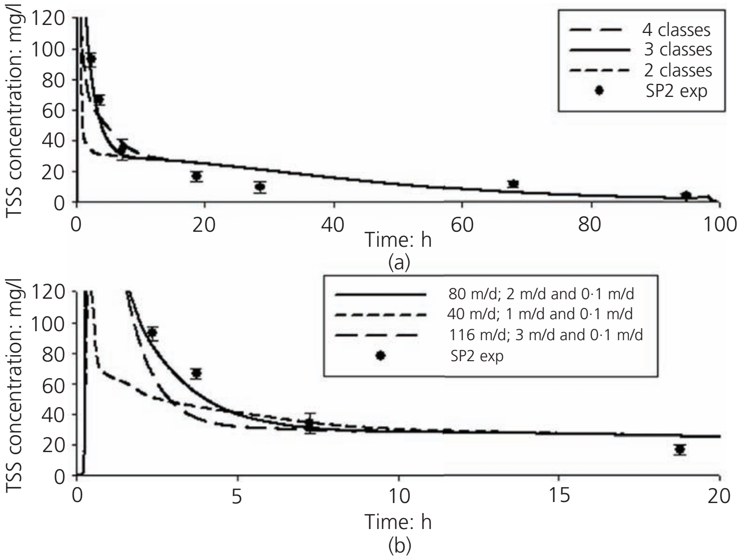

Figure 8. Simulation comparison for the 9 July 2010 sampling campaign with (a) different numbers of classes and (b) different settling velocities of the three particle classes

OPEN AND CLOSED OUTLET RESULTS

Figure 9 presents simulation results for the two open outlet events (Table 1). A good fit with the outlet TSS concentrations can be observed even though the first measured outlet TSS point for 11 July 2009 and peaks at the outlet for 18 July 2009 cannot be reached. For the first point for 11 July 2009, it is possible that the sediments already present in the basin before the event are resuspended by the first flow. Note that because events are simulated independently, it is difficult to evaluate the initial sediment mass available for resuspension at the beginning of the event. Therefore, this phenomenon cannot be reproduced despite the implementation of a mixing flow between layers (mixing flow explanations follow). The composite sample collected for the ViCAs tests is made by sampling 1 litre of the influent at different times during the run-off. As the determination of the flow to determine when a sample is to be added to the composite sample is visual, the

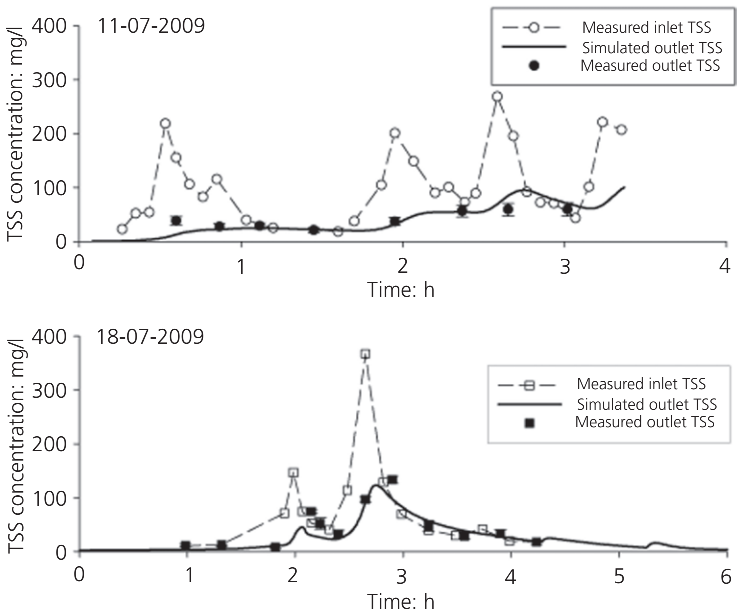

Figure 9. Measured and simulated TSS concentration results for both the 11 and 18 July 2009 open outlet events

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composite sample of the 18 July 2009 event may not have been completely representative. As for this specific event more 1-litre samples have been collected during the peak flows, the ViCAs results may have overestimated the fraction of particles with high settling velocities. The practical difficulties of collecting samples that represent the whole distribution of particles (not possible with a standard automatic sampler) over the whole duration of the rain event create a risk of non-representative samples. The inlet concentration is also highly variable, and it is thus more difficult to get a representative sample. This results in a lower concentration of particles that remain in suspension and an underestimation of the simulated outlet peaks. The composition of the sample used to run the ViCAs test is thus crucial for the modelling results and should get proper attention during the experimental work. Another way to deal with this issue is to make multiple composite samples for different phases of the event (first flow, peak flow and end of run-off) and perform ViCAs tests on each of them. The result would allow for a better description of the particle settling characteristics of the inlet but at the expense of much more laboratory work.

Figure 10 shows the simulated TSS concentration for the closed outlet event. Figure 10(a) presents results for subbasin 3, layer 2, which corresponds to sampling point 1 in Figure 1(b). Figure 10(b) presents results for subbasin 4, layer 3, which corresponds sampling point 2. By convention, the water surface is at the top of layer 1. In view of the uncertainty in the ViCAs tests, the TSS measurements and the sampling method, it can be concluded that the model is able to reproduce the water quality, both in the basin and at its outlet.

Regarding the ViCAs test, it was already mentioned that the sample taken to perform the test has to be representative of the entire run-off. It could be interesting to make more than one ViCAs test per event to evaluate whether the simulation results could be improved.

While measurement and sampling uncertainty have already been discussed, the modelling of a system with vertical profile sampling is subject to another difficulty – that is, the choice of the layer for comparison of the simulation and measurement data. Actually, samples could not be always taken at the same water depth. It was decided to compare the measurements with the simulations of the first three layers because the samples were taken near the surface (between 10 and 20 cm). The modelled concentrations in the different layers show a large heterogeneity along the depth of the water column and in the different subbasins. To calibrate the model better, it would thus be interesting to collect and analyse samples at different water depths to obtain the concentration profiles. However, the challenge will be to develop a non-invasive sampling method that does not disturb the concentration profile or the settling conditions around the sampling point.

In Figure 10(c), it can be observed that the measured TSS concentration data gradually increase during the emptying of the basin. This is explained by resuspension of settled particles by the emptying flow that is leaving an ever smaller remaining volume of stored water. A mixing flow between the layers has been implemented to reproduce this phenomenon. Figure 11 presents the

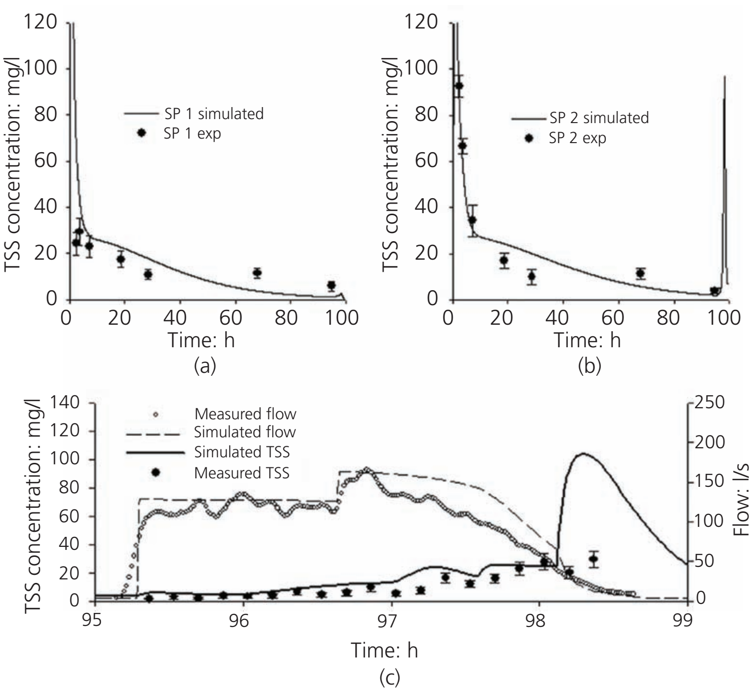

Figure 10. Measured and simulated results for the 9 July 2010 closed outlet event. Measured and simulated TSS concentration results in the basin at the sampling point (a) near the inlet and (b) near the outlet. (c) Measured and simulated TSS concentrations and flows at the outlet during the emptying of the basin

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simulated outlet TSS concentration during the emptying of the basin for the 9 July 2010 event with and without mixing flows. It is obvious that the mixing flow is essential to obtain good results.

The mixing flow has been defined by Equation 3, which relates the mixing to the volumetric flow in a subbasin – that is to the inflow (Q_{in}) and the outflow (Q_{out}) of the subbasin considered and considering the volume into and out of which these flows occur.

$$Q_{mix} = Q_{mix\_max} \frac{(Q_{in} + Q_{out})/V^2}{K_{mix} + (Q_{in} + Q_{out})/V^2} \quad (3)$$

with V as the water volume in the subbasin and Q_{mix_max} and K_{mix} as calibration parameters.

Equation 3 is a saturation function with a global variable ((Q_{in} + Q_{out})/V^2), which takes care of the water flowing through the subbasin responsible for the mixing and the water volume which is opposed to the mixing. The square power gives a strong resuspension-countering effect when the water volume starts to increase, and it was found that this squared function works for both open and closed outlet events. Moreover, considering the subbasin state variables (Q_{in}, Q_{out} and V) allows local calibration parameters to be found (Table 2). Using local conditions is really important to reproduce morphological specificities. For example the effect of the channel present in the studied basin is reproduced by setting mixing parameters to zero for both subbasins 2 and 3. The TSS mass available for resuspension is then limited, and the high peak at the end is weakened. This peak is due to the end of the emptying of subbasin 3. As long as it is not empty, the emptying flow is distributed between subbasin 3 and 4, depending on their surfaces. Because the surface of subbasin 3 is much larger than that of subbasin 4, its outflow is relatively small. When subbasin 3 is empty, all the emptying flow is flowing through subbasin 4 and its mixing flow becomes instantly large. Consequently, it is resuspending many sediments because the water volume is no longer large enough to dampen the mixing energy induced by the flow.

Conclusions

This paper presents both experimental and modelling results. By sampling the water column during storage of the run-off at different locations throughout the storm water basin, it has been shown that storm water basins are characterised by a spatial heterogeneity of TSS concentrations during the first hours of retention. Thanks to settling, the TSS concentrations become uniform across the basin with increasing retention time. A water quality model based on particle classes characterised by settling velocities experimentally determined with ViCAs tests has been developed. It is able to reproduce the TSS concentrations both inside and at the outlet of a storm water basin, for both open and closed outlet configurations. It is essential that a composite inflow sample is used for the ViCAs tests to be representative of the entire run-off. The fractionation of the storm water basin influent particles that is used to create the model input file is also crucial to obtain good results. According to the results obtained in the present study, the smallest number of classes giving good fit is three, characterised by settling velocities of 80, 2 and 0·1 m/d. Finally, a resuspending mixing flow between the stagnant sediment layer and water column layers above had to be implemented. The mixing intensity is a function of the inflow and outflow of the subbasin and the (square of the) water volume in the subbasin. With this model, the TSS concentration time series during the emptying of the basin could be well described.

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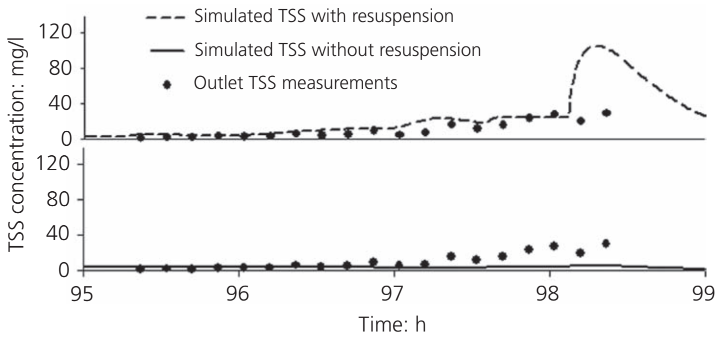

Figure 11. Simulation of TSS measurements with (up) and without (down) resuspension mixing flows

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