A new dynamic stormwater basin model as a tool for management of urban runoff

Un nouveau modèle dynamique de bassin d'orage comme outil de gestion des eaux de ruissellement urbaines

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RÉSUMÉ

Afin d'améliorer la qualité des rivières, tout en garantissant la sécurité des populations, le projet auquel se rattache l'étude présentée dans cet article tente de définir des règles de contrôle en temps réel pour la gestion de bassins d'orage équipés de vannes en sortie. Ces règles doivent permettre d'augmenter le temps de rétention de l'eau dans le bassin et ainsi permettre une décantation des particules les plus petites et des polluants associés. Pour cela, un nouveau modèle dynamique de bassin d'orage a été développé pour simuler le comportement des différents polluants associés aux particules. Ce modèle se base sur la superposition de couches complètement mélangées et inclut le comportement et les processus reliés aux polluants associées aux particules, dépendant notamment des différentes vitesses de sédimentation de ces dernières. Après la description du modèle, les résultats de simulation d'essais ViCAs, représentant les comportements des particules en conditions quiescentes sont présentés. Ces simulations ont permis de valider les concepts développés. Par la suite le comportement dynamique de quatre types de polluants dans des conditions hydrauliques plus contraignantes est décrit, avant de conclure sur les perspectives que peut offrir le modèle en termes de rapidité de calcul et de complexité des processus modélisables.

ABSTRACT

To improve the rivers quality, while guaranteeing the population safety, the present study is part of a larger project defining rules for real-time control of stormwater basins upgraded with sluice gates on the outlet. These rules have to allow increased water retention time to allow settling the smallest particles and the associated pollutants. For that purpose, a new dynamic model of stormwater basin has been developed to model the behaviour of various pollutants associated to particles. This model is based on the superposition of completely mixed layers and includes the behaviour and the processes connected with pollutants associated with particles, depending on different particle settling velocities. After describing the model, results of ViCAs experiment, representing the behaviour of particles for quiescent conditions are presented. These simulations allowed to validate the developed concepts. The dynamic behaviour of four types of pollutants for more complex hydraulic conditions is also presented before concluding on the perspectives that can be offered by this model in terms of computational speed and complexity of processes.

KEYWORDS

Modelling, Particles Behaviour, Settling Velocities, Stormwater, Real Time Control

1 INTRODUCTION

Stormwater in urban areas can cause serious flooding problems. At the same time it is common knowledge that stormwater contains a considerable amount of suspended solids (SS) and pollutants associated with it (metals, pathogens...) (Pettersson 2002; Vaze and Chiew 2004; Characklis et al. 2005). To deal with flooding problems e.g. an induced by increasing impervious area, stormwater basins have been built to reduce negative hydraulic effects on the river's morphology and ecology.

The present study is part of a larger project in which a new approach is developed that upgrades existing stormwater retention devices designed for flood risk control with a management system to improve the eco-hydraulics of the receiving water body (Muschalla et al. 2009). The idea is to control a sluice gate at the outlet of stormwater basin in real time to enhance the removal efficiency of fine particles by increasing the retention time of stored stormwater and reducing the peak flow released in the receiving river at the same time. Some earlier studies have successfully tested the idea to equip stormwater basins with sluice gates to control the outflow. However, these studies have focused on the basin only without considering the state of the receiving river (Jacopin et al. 2001; Middleton and Barrett 2008).

For the development of this eco-hydraulic driven real-time control (RTC) of stormwater basins an integrated model for the river and drainage system is needed. Control rules have to be developed and validated using long term simulations and considering multiple objectives e.g. flood protection and river water quality standards.

In this context, the quality model of the stormwater basin is a key element. The computation has to be fast enough to allow performing multiple long term simulations. At the same time multiple pollutants (particles, pathogens, heavy metals) and processes related to them (adsorption/desorption, settling, disinfection) have to be considered to characterise the water quality of the basin's effluent for different environmental conditions.

Existing computational fluid dynamic (CFD) models for stormwater basins deal with the complex hydraulic conditions and explain where and when sediments will settle (Torres 2008). Due to their complexity and computing time these types of models are not appropriate. Then models based on a completely stirred tank reactor approach (CSTR) can be applied (Ferrara and Hildick-Smith 1982; Wong et al. 2006).

Here we introduce a new modelling concept by transferring the concept of layers from wastewater settler modelling (Vitasovic 1989) to stormwater modelling. In our concept, each layer is modelled as a CSTR. The superposition of these layers allows creating a gradient of concentrations over the water column in the basin. The chosen model allows to easily include reactions in each layer to reproduce the behaviour of the different pollutants.

This paper concentrates on the description of the basic model formulation and discusses how this model can reproduce the behaviour of particulate pollutants in a stormwater basin. Experimental results used for the validation of the model concepts are presented. In addition the behaviour of pollutants under different hydraulic conditions is discussed. The possibilities of further model extensions to better reproduce the complex hydraulic and quality phenomena of a stormwater basin are identified.

2 MATERIAL AND METHODS

2.1 Model description

The model developed is composed of three submodels: a hydraulic model, a soluble pollutant model and a particulate pollutant model. The equations related to these three models will be explained in the next paragraphs.

2.1.1 Hydraulic model

As stated before, this model is based on the concept of completely mixed layers developed by Vtasovic (1989) for waste water treatment plant's secondary clarifiers. The advantage of this concept is that it allows the modeller to create a gradient of concentrations along the height of the basin with simple equations. However this model is made for a settler that has a constant volume of water. In a stormwater basin, the volume is variable depending on the runoff generated by the rain. To take this phenomenon in account, the new model uses a mass balance of water, with a maximum physical volume defined by the stormwater basin's volume, at which point it overflows.

Figure 1 explains the different parts of the hydraulic model. On the upper part, the volume of the basin is defined by the maximum height (Hmax). If the water reaches this height, overflow occurs (Q_overflow). In the basin, the volume of water is defined by the integration of the balance between the water coming in and the water going out (1).

$$dV/dt = Q_{in} - \left(Q_{draw} + Q_{overflow}\right) \tag{1}$$

It is then divided in N layers. The right and the left part show a representation of the evolution of the water volume between t and t+Δt during filling. It can be seen that the volume of each layer is always changing with time but also, that the layer volumes are always the same at any time. Each layer is regulated by its own inflow and outflow which allow different hydraulic conditions to be represented. For example during a large rain event the outlet pipe can be submerged and the water is then going out from the basin through the bottom layers but not through the top layers. Turbulences created by this phenomenon needs to be represented because soluble or particulate pollutants concentrations will be affected. To take care of this phenomenon, flows between layers have also been implemented. The lower part of Figure 1 shows which type of flow is taken into account between layers.

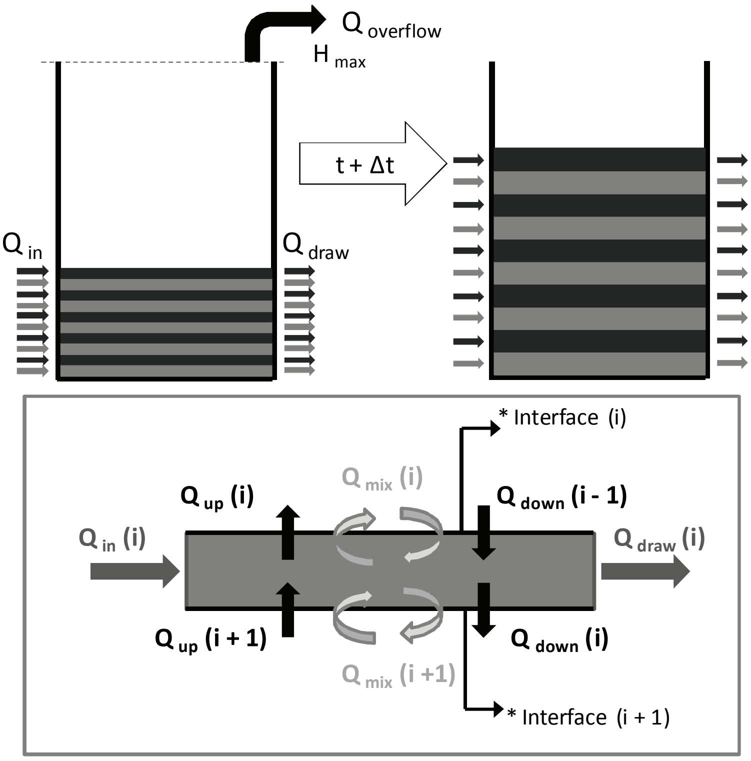


Figure 1 : Overview of the different variables in the hydraulic model developed

There is flow coming from the bottom to the top (Q_up), flow coming from the top to the bottom (Q_down) and mixing flow around the layer interface (Q_mix). For equations presented below, Q_mix will always be included in Q_up and Q_down in addition to the part coming from Q_in or Q_draw as shown in equations 2 and 3.

$$Q_{up}(i) = Q_{mix}(i) + MAX\left[\left(\sum_{j=i}^{N} Q_{in}(j) - \sum_{j=i}^{N} Q_{draw}(j)\right);0\right] \tag{2}$$

$$Q_{down}(i) = Q_{mix}(i+1) + MAX\left[\left(\sum_{j=i+1}^{N} Q_{draw}(j) - \sum_{j=i+1}^{N} Q_{in}(j)\right);0\right] \tag{3}$$

In the next paragraphs the index "s" is related to soluble pollutants, index "x" is related to particulate pollutants, C is the pollutant's concentration; "in" is related to the influent of the layer; A is the area of the basin and "n" is the index of the layer considered.

2.1.2 *Soluble pollutant model*

The variation of soluble pollutant mass (M_s) can be calculated by a mass balance between what is coming in and what is going out from the layer, considered as a completely stirred tank reactor (CSTR).

$$\begin{aligned} dM_s(i)/dt = {} & Q_{in}(i) \cdot C_{s\,in}(in) - Q_{draw} \cdot C_s(i) - Q_{up}(i) \cdot C_s(i) - Q_{down}(i) \cdot C_s(i) \\ & + Q_{up}(i+1) \cdot C_s(i+1) + Q_{down}(i-1) \cdot C_s(i-1) \end{aligned} \qquad (4)$$

This equation holds for constant volume. In the hydraulic model developed before the total volume and the layer interface's position are changing during filling and emptying of the basin. To take this phenomenon in account, the velocity of the movement up or down of the layer's interface is defined as $v_{interface}$. To complete the model (4) for varying volume, it is necessary to add equation (5) to equation (4), during filling ($v_{interface}$ positive) and equation 6 during emptying ($v_{interface}$ negative).

$$v_{Interface}(i) \cdot A \cdot C_s(i-1) - v_{Interface}(i+1) \cdot A \cdot C_s(i) \qquad (5)$$

$$v_{Interface}(i) \cdot A \cdot C_s(i) - v_{Interface}(i+1) \cdot A \cdot C_s(i+1) \qquad (6)$$

2.1.3 *Particulate pollutant model*

A particulate pollutant is defined by its ability to settle. This means that the pollutant has its own settling velocity (v_x, positive when oriented from the top to the bottom of the basin) and the movement of this pollutant depends on the difference between this velocity and the upward velocity of the water. Equation 7 presents which amount of particulate pollutant (B) coming from the top or the bottom layers contributes to the mass variation in the layer n depending on the upward velocity of the water. Max and Min functions are used to control the sign and the elements considered in term of the relative settling velocity of particles.

$$\begin{aligned} B = {} & -A \cdot C_x(i) \cdot MAX\left[\left(v_x - Q_{up}(i+1)/A\right); 0\right] + A \cdot C_x(i) \cdot MIN\left[\left(v_x - Q_{up}(i)/A\right); 0\right] \\ & -A \cdot C_x(i+1) \cdot MIN\left[\left(v_x - Q_{up}(i+1)/A\right); 0\right] + A \cdot C_x(i-1) \cdot MAX\left[\left(v_x - Q_{up}(i)/A\right); 0\right] \end{aligned} \qquad (7)$$

For layer 1, there is no Q_{up}. This term is then replaced by $Q_{overflow}$.

The variation of particulate pollutant mass (M_x) can then be calculated by a mass balance between what is coming in and what is going out from the layer, considered as a CSTR.

$$\begin{aligned} dM_x(i)/dt = {} & Q_{in}(i) \cdot C_{x\,in}(i) - Q_{draw}(i) \cdot C_x(i) \\ & -Q_{down}(i) \cdot C_x(i) + Q_{down}(i-1) \cdot C_s(i-1) + B \end{aligned} \qquad (8)$$

In the same way than for soluble pollutants, it is necessary to add equation (9) to the equation (8) during filling ($v_{interface}$ positive) and equation (10) during emptying ($v_{interface}$ negative) to consider the movement of layer's interfaces in the mass balance.

$$v_{Interface}(i) \cdot A \cdot C_x(i-1) - v_{Interface}(i+1) \cdot A \cdot C_x(i) \qquad 9$$

$$v_{Interface}(i) \cdot A \cdot C_x(i) - v_{Interface}(i+1) \cdot A \cdot C_x(i+1) \qquad 10$$

2.2 ViCAs experiments

To determine settling velocities three ViCAs experiments (Chebbo and Grommaire 2009) have been conducted on composite samples of 3 different rain events. Flow-proportional composite samples of the influent of a stormwater basin in Quebec City (Muschalla et al. 2009) were collected by taking several 1L samples (around 25 samples for each event). The ViCAs experiments are started by filling a settling column of around 60 cm height and 2.5L volume. At predefined time intervals the cumulative mass settled at the bottom of the column is measured. In the subsequent mathematical fractions of total suspended solids for different settling velocities are determined.

To validate the basic model and to verify the derived classes of sedimentation velocities simulations were performed. The ViCAs column in the developed model was divided into 9 layers. A 10th layer was used to represent the plate that collects the sediments at the bottom of the column.

2.3 Model implementation

State of the art software packages used in sewer modelling (e.g. EPA's SWMM5, (EPA 2008)) only allow including algebraic equations to describe quality processes in stormwater management devices. To overcome these limitations the developed model has been implemented in the WEST modelling and simulation software (MOSTforWATER, Kortrijk, Belgium) which is used for wate water treatment plant modelling and integrated modelling. WEST allows to efficiently solve ordinary differential equations and it offers the possibility to easily implement processes equations by matrix based description of kinetics.

2.4 Theoretical simulation

In order to demonstrate the potential of the new model and to show the behaviour of the different types of pollutant, a hypothetical situation was simulated. By convention layer 10 is at the bottom and layer 1 is at the top of the basin. Four types of pollutants have been selected; a soluble pollutant and three particulate pollutants attached to particles with a settling velocity respectively higher, equal and lower than the upward velocity of the water (respectively v_x high, v_x medium and v_x low). A basin of 3.000 m³ was set, 2/3 full. A 1.000 m³/d flow of clear water was assumed to enter at layer 10 to fill the basin and leading to an overflow after 1 day. Table 1 shows the initial distribution of the different types of pollutant in the different layers. These layers have been chosen to show the behaviour of the different kinds of pollutants regards to their own settling velocities for the flow condition simulated. The initial masses were all the same with 5.000 g.

Type of pollutant	soluble	v_x high	v_x medium	v_x low
Layer	9	1	4	9

Table 1: Distribution of the different kind of pollutants in the layers at t=0

3 RESULTS AND DISCUSSION

3.1 Simulation of the ViCAs experiments

A ViCAs experiment occurs under ideal conditions of settling without turbulence and it is the nearest to reproduce the settling conditions of a stormwater basin with a closed outlet. To test the model's capacity of predicting the quality of the water after different settling times with a closed outlet, ViCAs experiments were simulated in terms of the cumulative settled mass and the concentration of TSS remaining in the column at the end of the experiment.

Results of ViCAs experiments were used to define the different masses and settling velocities of particulate pollutants for the model. Table 2 shows an example of the distribution which was made for the ViCAs experiment of the 21st of August 2009. ViCAs results give a fraction (F) of the initial TSS concentration in the column that has a settling velocity less than the height of water divided by the settling time (v_s). The mass of particles with a velocity higher than v_s is then (1-F).TSS. By calculating the different masses for each interval of velocities, it is possible to recompose an input for the model with the mass corresponding to each settling velocity.

Figure 2 compares the measure and simulated cumulative mass at the bottom of the ViCAs's column. The model fed with the 11 classes of settling velocity (---) fitted the data quite well even if at the end the simulated settled mass is a little bit higher than the experimental obtained mass. This difference depends on the mass balance obtained in the experiment. Good experimental work can lead to a mass balance closing within ±15% between the initial mass in the column and the sum of the cumulative settled mass and the final mass in the column (Chebbo and Grommaire 2009). The choice was made to use the initial TSS concentration as basis to calculate the different masses of the different velocity classes for the input of the model because it is the easiest parameter to characterize a rain event's run-off. According to that choice, the mass balance of the ViCAs test determines the precision of the model on the final concentration of the simulated experiment. Actually, after an infinite settling time, the final mass in the simulated column is the mass of the last class (v_x=0 m/d). Hence that mass can be different to the experimental final mass in the column because it is recalculated from the initial TSS concentration. The difference is connected to the mass balance of the experiment. It is then important to keep the mass balance of the ViCAs below the 15% precision mark.

ViCAs results		**Model input for 11 velocity classes**		**Model input for 4 velocity classes (a)**		**Model input for 4 velocity classes (b)**	
Settling velocity	Fraction with settling velocity smaller than	Settling velocity class	Mass of particulate pollutant	Settling velocity class	Mass of particulate pollutant	Settling velocity class	Mass of particulate pollutant
m/h		m/h	Mg	m/h	mg	m/h	mg
17.75	0.93	>17.75	10.9	>17.75	10.9	>0.58	50.8
5.92	0.88	5.92-17.8	7.8	0.58-17.75	39.9		
2.54	0.83	2.54-5.92	9.0				
1.18	0.76	1.18-2.54	10.7				
0.58	0.69	0.58-1.18	12.4				
0.28	0.60	0.28-0.58	13.3	0.023-0.58	58.9	0.14-0.58	27.1
0.14	0.52	0.14-0.28	13.8				
0.062	0.42	0.062-0.14	15.2			0.023-0.14	31.4
0.023	0.32	0.023-0.062	16.2				
0.019	0.31	0.019-0.023	2.7	< 0.023	52.4	< 0.023	52.4
		<0.019	49.7				

Table 2: Example of velocities classes distribution between ViCAs experiments and model input

To simplify future calibrations of the model it may be useful to reduce the number of classes. Actually, the ViCAs experiments give n settling velocities for n plates collecting the settled particles. This means that it is possible to define n+1 settling velocity classes. For the example of Table 2: for 10 plates, 11 settling velocity classes can be defined. In views of modelling the different pollutants and processes associated with the different particle classes, this means that it is necessary to define the pollutant associated to each class of particles. For 11 velocity classes, this means it is necessary to define the amount of metals and pathogens associated with the 11 classes of particles, on top of the dissolved fraction. To avoid this complexity, the quality of the model with a reduced number of velocity classes was tested. A test was made with 4 velocity classes. Once the 4 velocity classes defined, the mass for each class was calculated by summing of the masses of the experimental classes that have a higher settling velocity (Table 2).

Figure 2 presents the simulation results obtained for 2 different sets of 4 classes. It can be seen that the choice of the settling velocity classes is very important for the modelling quality. Even if the pattern is really different the square roots of the sum of the squared errors are nearly the same (46.5 compare to 42.5). Actually, when the velocity classes are chosen to take into account the particles with fast settling velocities, the simulation is better at the low settling times but cannot follow the results from 14 min to 1.08 d. In the context of the stormwater basin modelling with closed outlet it is however more important to follow the settling over a long time than for the first 15 min. In this case, the 4 classes that do not account in detail for the particles with fast settling velocities is a better choice. It can give a better simulation of the evolution of the concentration in the column vs time.

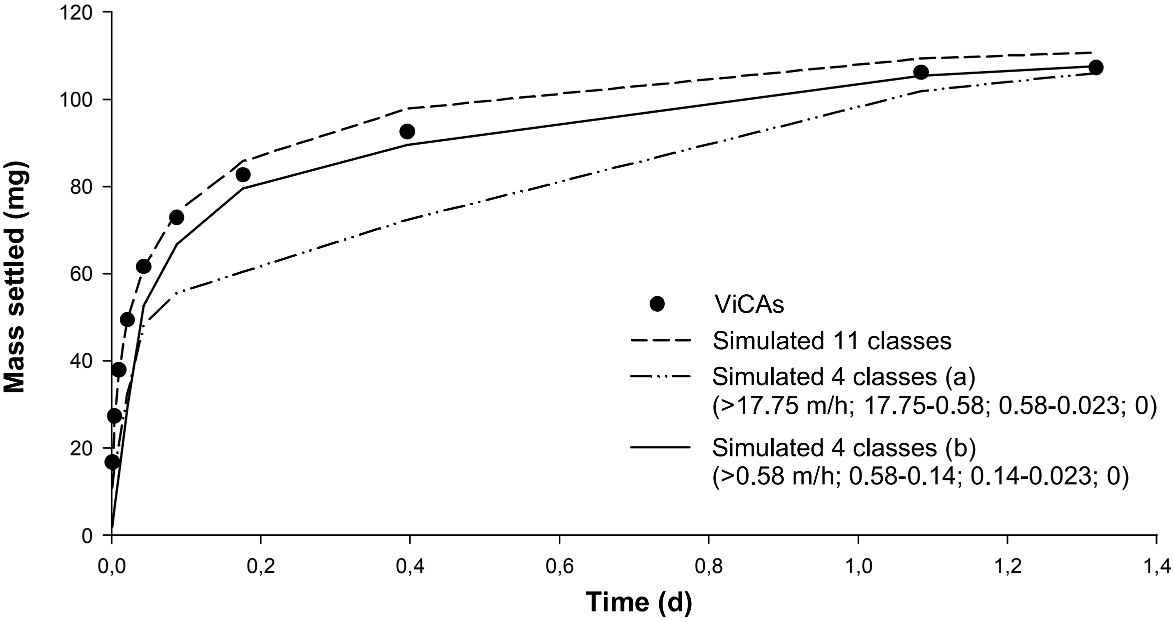


Figure 2: Cumulative mass at the bottom of a ViCAs column compared to the simulation results for different numbers and types of particle classes

Once the 4 classes chosen, it was also evaluated whether the same 4 classes can give the same results for different ViCAs experiments check whether the same velocity classes could be used for the different rain event that occurred during a long term simulation. Figure 3 presents simulations for 2 other ViCAs experiments. The final TSS concentration in the column is given in the legend of the figure. It can be seen that the concept is working unless the mass balance is kept within the 15% (data not shown). The final simulated and experimental concentrations are also similar. If the mass balance of the ViCAs experiment is not good enough, the final concentration and settled mass are really variable (data not shown).

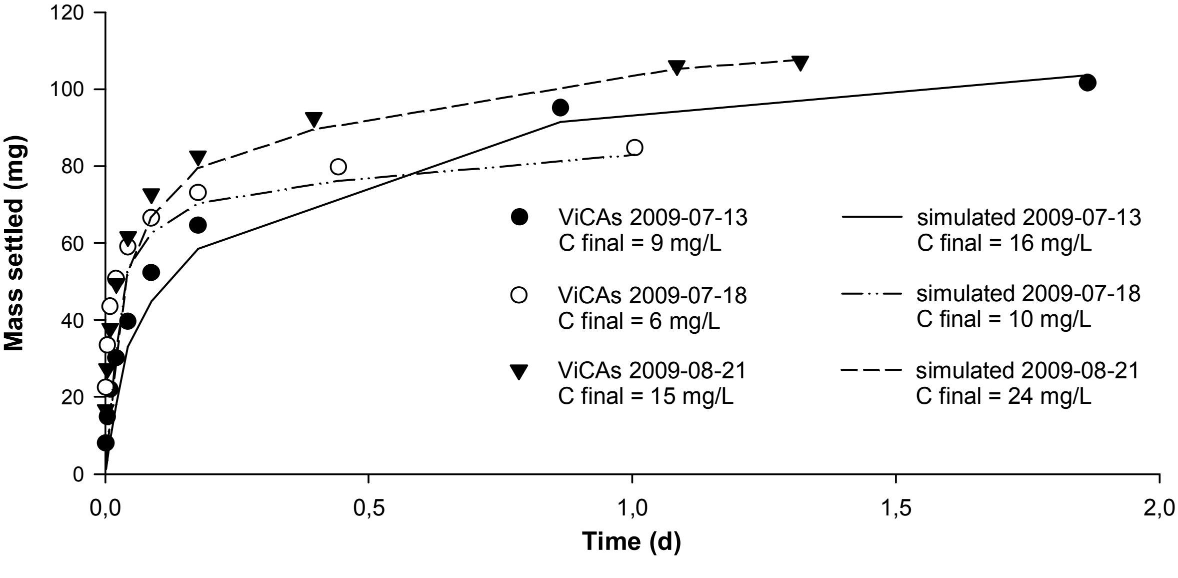


Figure 3: Cumulative mass for different ViCAs experiments compared to simulated results with the new model

3.2 Pollutant behaviour

The new model has demonstrated its ability to fit experiments data for quiescent conditions (without any water movement). This section illustrates the behaviour of the pollutants in the stormwater basin when exposed to a filling phase with clear water entering at the bottom (layer 10). As presented on Figure 1, the inflow is increasing the volume of the layers and the stormwater basin overflows after 1 day. Figure 4 presents the dynamics of 4 types of pollutants by drawing the mass of the different pollutants in each layer after different settling times.

It can be seen that for soluble pollutant (a), the pollutant is pushed from layer 9 to the surface with a small part going to layer 10 due the movement of the interface between layers 9 and 10 (equation (5)). For the other layers the behavior is the same as for a soluble pollutant in a plug flow reactor. When the pollutant reaches layer 1 and the basin overflows, the total mass of pollutant starts to decrease in the basin.

The particulate pollutant with low v_x (b) has the same behaviour as the soluble pollutant. Nevertheless, the total mass at the end of the simulation is higher than the mass of soluble pollutant (3500 g vs 1873 g) because of the settling of the particles that keeps them in the basin.

The particulate pollutant with high v_x (c) is settling from layer 1 to layer 10 and all particles accumulate in the 10th layer. Finally the last type of pollutant with medium v_x (d) is supposed to stay in the same layer given that its settling velocity equals the upward water velocity. However it can be seen that the mass is dispersed among the layers around layer 4 because the layer volumes increase and the interface moves into the depth where another layer was previously located, capturing or losing particles. When the basin is overflowing after 1 day, the layer's interfaces no longer moves and the mass of the pollutant does no longer vary in the layers where the particles are. This is a dispersion effect generated by the fact that layers are completely mixed.

Figure 4 shows an ideal case study. The behaviours of the different pollutants and of the flows in a real stormwater basin are different because of mixing, the position of the inlet and outlet pipes and other environmental conditions. The aim of this example was to show the potential of the new model. Actually, if the inlet pipe has a fixed position, a mechanism can be implemented to distribute the inflow over more than one layer at the bottom of the basin. During filling, some inflows into the upper layers can be set to 0 because the layer interface reaches a position above the top of the pipe. Also, mixing flows can be defined around the inlet or outlet layers to create some mixing due to the inflow or outflow. Finally, to model the heterogeneity of a stormwater basin, more than one basin could be connected together with different characteristics or configuration (mixing, volume, processes...).

3.3 Next steps

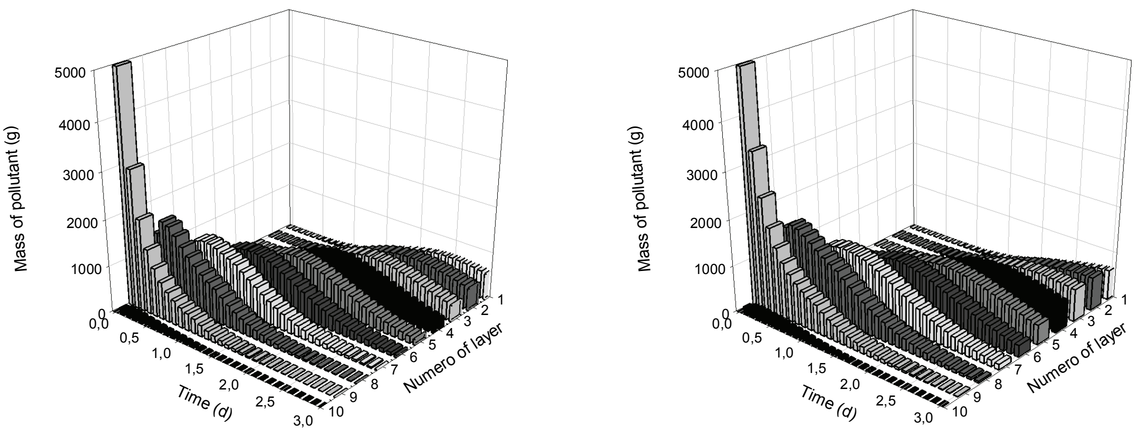
At the moment of writing this paper, the connection between different basins is not yet developed. However it is necessary to allow connections between layers to reproduce the stormwater basin's heterogeneity in the model. Also reactions between particulate and soluble pollutants, environmental effects like UV disinfection or plant effects have to be implemented. Regarding the different kinds of particles, this model provides many options. For example it is well known that metals are adsorbed on the small particles with the lowest settling velocity (Pettersson 1999). With this model, it is also easy to introduce different adsorption coefficients for different types of particulate pollutants.

Once implemented completely it will be important to calibrate and validate the parameters of the model with experimental data. The last summer was focused on the sampling of different events with open and closed outlet to provide the data for this step.

This model is developed for use in RTC development. The computational time is then an important factor. Compared to CFD modelling which may need more than one day to simulate one event (Torres 2008), this model needs computational times around a second to provide the data presented in Figure 4. Even with an increased complexity of the model by inclusion of different reactions and different connected basins the computational time will not increase too much. This computational time can then be used for long-term simulations and will allow testing different RTC rules of a stormwater basin upgrade with a sluice gate.

a) Soluble pollutant

b) Particulate pollutant (Vx low)



c) Particulate pollutant (Vx high)

d) Particulate pollutant (Vx medium)

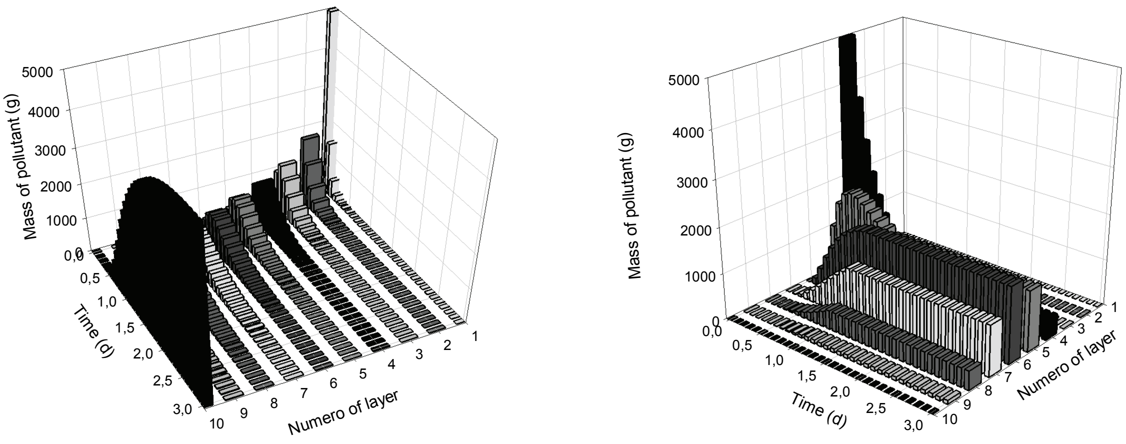


Figure 4 : Simulated behaviour of different types of pollutants in the developed model: Soluble pollutant and particulate pollutants with high (higher than the upward water velocity), medium (equal to the upward water velocity) and low (lower than the upward water velocity) settling velocity (v_x)

4 CONCLUSION

This paper has shown that the developed model using a series of completely mixed layers and different types of pollutant is able to reproduce the results from ViCAs experiments reproducing ideal settling conditions occurring in a stormwater basin modified by closing the outlet. This model has been able to reproduce data from different ViCAs experiments with a limited number of velocity classes. This allows for a simpler calibration by limiting the number of classes that have to be characterised. The model also allows reproducing complex hydraulic behaviour and various types of pollutants present in a stormwater basin. By adding processes between the different kinds of pollutants and connecting different basins together, it will be possible to reproduce the complexity of a stormwater basin. Finally the computational time necessary to run the model is such that it can be used for long-term simulation and development of RTC rules.

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